Volume XLIII November 1948 Number 7

Economic Geology

and the

Bulletin of the Society of Economic Geologists

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PUBLISHED SEMI-QUARTERLY

Five Dollars a Year, One Dollar a Copy

THE ECONOMIC GEOLOGY PUBLISHING COMPANY

Printed by Lancaster Press, Inc., Prince and Lemon Streets, Lancaster, Pa.

Entered as second-class matter, March 30, 1906, at the Post Office at Lancaster, Pa., under the Act of Congress of March 3, 1879

Economic Geology

and the

Bulletin of the Society of Economic Geologists

Issued Semi-Quarterly and sent to subscribers on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15.

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Foreign Agents. Geo. Allen and Unwin, Ltd., No. 40 Museum St., London, W. C. 1, British Agents.

Indexed in the Industrial Art Series.

LANCASTER PRESS, INC., LANCASTER, PA.

ECONOMIC GEOLOGY

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TRANSPORT AND DEPOSITION OF THE NON-SULPHIDE VEIN MINERALS.

III, PHASE RELATIONS AT THE PEGMATITIC STAGE.

F. GORDON SMITH.

ABSTRACT.

The problem is raised as to whether a granitic magma under high pressure conditions would form a water solution immiscible with the residual silicate solution as crystallization proceeds. The composition of the rest-magma, after 96 percent crystallization of a magma which contained 2 percent of water, is calculated. Experiments showed that the rest-magma would be separated into two liquid phases between 290° and 550° C. under a pressure equivalent to a depth of 10 kilometers. A two-component approximate phase diagram, based on data of R. W. Goranson and analyses of the immiscible liquids, is deduced. It is concluded that granitic magmas form two immiscible residual solutions during a stage in their crystallization.

IN the first paper of this series (13),[1] the sequence of crystallization of vein minerals was considered to be due to decreasing solubility of certain components and to decomposition of complex ions of other components in a water solution, but the sequence was considered to be continuous. However, there is a body of field data which strongly suggests that there is a discontinuity of vein types, the pegmatite veins being quite distinctly different in mineralogy, and time or place of deposition from the quartz-sulphide veins. There also exists some laboratory experiments which show that fluid immiscibility between silicates and water may occur over a definite range of temperature, pressure, and composition. Therefore the next step seemed to be to consider the following question: does fluid immiscibility develop during the cooling of a deep-seated magma, and if so, what are the partition relations of the important components between the two fluids? [2]

[1] The numbers in parentheses refer to bibliography at end of paper.

[2] In the following discussion, the term liquid wil be used for a fluid of high density, regardless of its temperature, since liquids undergo apparently no discontinuity of properties at the critical temperature; the discontinuity appears, if at all, at some lower temperature which is a function of the degree of filling when the volume is constant.

The problem of the sequence of phase changes has received a considerable amount of theoretical analysis but very little experimental data is available. No attempt will be made to review this study, but the writings of Vogt (15, 16), Niggli (11, 12), Morey (10), Fenner (2), Bowen (1), and Graton (5) cover much of the development and analysis of the recent concepts. For experimental data, the study of the system potassium silicate-water by Morey (9) and that of the system granite-water by Goranson (3) are of special importance.

Goranson (3) found that a liquid of the composition of a typical granite can dissolve water, the amount dissolved being a function of temperature and pressure. He found that there is an upper limit to the solubility of water in granite liquid, the amount being approximately 10 percent when under a very great pressure. Thus fluid immiscibility between water and magma has already been sufficiently proved. However, if we follow the history of a granite magma containing much less than 10 percent water (as the temperature falls and crystallization of the granite proceeds), the residual liquid must change in composition, and the solubility of water in the residual liquid will be different from that in the initial liquid. Normally, as magmatic crystallization proceeds, the residual liquid becomes richer in K_2O, Na_2O, SiO_2 and in the rarer components such as B_2O_3, P_2O_5, Cl, F, so that one would expect the solubility of water in the residual liquid to increase as crystallization proceeds. This also follows from the experimental results of Morey (9), who demonstrated that there is no liquid immiscibility between water and potassium silicate, as long as the pressure is more than 340 bars. But does the solubility of water in the residual liquid increase as fast as the increase in the concentration of water due to crystallization of silicate minerals?

Let us consider a granite magma containing 2 percent of water crystallizing 10 kilometers below the surface. When the granite is 50 percent crystallized, the water content in the residual liquid is 4 percent, and when 80 percent crystallized, it is 10 percent. After that the percent of water in the residual liquid rises more quickly, as is shown in Table 1 below. We know that the residual liquid could dissolve at least about 10 percent of water, and it is reasonable to suppose that the last part of the silicate liquid could dissolve somewhat more than 10 percent, but it seems improbable that it could dissolve an unlimited amount of water. However, this can be tested by experiment.

Before one can test whether or not the residual granitic liquid can dissolve an unlimited amount of water, it is first necessary to calculate the approximate composition of the liquid. If it is assumed that the granite has crystallized 96 percent, the residual liquid (or liquids) then contains 50 percent of water. All of the components of the granite which have not yet

TABLE 1.

RELATION BETWEEN THE FRACTION OF A MAGMA THAT HAS CRYSTALLIZED AND THE PERCENTAGE OF WATER IN THE LIQUID (OR LIQUIDS) REMAINING.

Percentage of magma crystallized	0	50	80	90	95	96	97	98%
Percentage of water in rest-magma	2	4	10	20	40	50	66.6	100%

started to crystallize will be likewise concentrated in the residual liquid. In Table 2 is given the estimated percentage of several representative fluxing components in the original granite magma (taking into account that during crystallization much of each is lost from the magma chamber due to the formation of pegmatite and quartz-sulphide veins, and in hot springs) and the corresponding percentage in the residual liquid after 96 percent crystallization of the granite. The choice of sodium or potassium to accompany the acid radicals was such that the final Na/K ratio of the total rest-magma was near unity. The total amount of the water soluble fluxes was estimated to be

TABLE 2.

Magmatic components very soluble in water	Estimated initial amount in granite magma	Calculated amount in granite rest-magma
K_3BO_3	0.5%	12.5%
Na_3PO_4	0.3	7.5
NaCl	0.2	5.0
NaF	0.1	2.5
Total	1.1%	Total 27.5%

27.5 percent of the residual liquid (or liquids). Let the remainder of the residual liquid (other than water) be of pegmatite vein composition, plus additional quartz to make the quartz-sulphide veins. The composition of pegmatite was taken to be similar to Grout's average (7). The silica content was increased from 71.8 to 80 percent, and the other components were decreased proportionally. The ferrous and ferric iron were added together and the minor components were left out. The result is shown in Table 3

TABLE 3.

ESTIMATED AVERAGE COMPOSITION OF THE PEGMATITE AND QUARTZ VEIN MATERIAL DEPOSITED (EXCEPT SULPHIDES).

Component	Percentage	Partial Percentage
SiO_2	80.0%	18.0%
Al_2O_3	11.0	2.5
K_2O	4.3	0.97
Na_2O	3.0	0.67
CaO	0.9	0.20
FeO	0.8	0.18
Total	100.0%	22.5%

below. Now if a mixture composed of water (50%), the components in Table 2 (27.5%), and the components in Table 3 (22.5%) is heated at a high pressure to a temperature where there is no solid phase, then the resulting liquid will be in either one or two phases, and the problem will be resolved.

A mixture of the compounds shown in Table 4 above was prepared. The total volume of the mixture in each experiment was such that a pressure of approximately 2,500 bars was developed at the temperature of heating. The pressure vessel was similar to that described previously (14), except that the graphite lining was 2 mm thick instead of ¼ inch thick. After the bomb

TABLE 4.

Calculated composition of residual liquid(s) after 96% crystallization of granite magma		Compounds added to the bomb to make a similar composition (Experiment P-8 as example)	
H_2O	50.0%	H_2O (distilled)	49.62 gm
K_2BO_2	12.5	H_3BO_3 (C.P.)	5.475
Na_3PO_4	7.5	$NaH(PO_3)_2$ (Baker)	5.18
NaCl	5.0	NaCl (C.P.)	4.60
NaF	2.5	NaF (C.P.)	3.12
SiO_2	18.0	SiO_2 (C.P., 22% H_2O)	28.82
Al_2O_3	2.5	Al_2O_3 (pure, ignited)	3.12
K_2O	0.97	KOH (C.P.)	16.37
Na_2O	0.67	NaOH (C.P.)	7.43
CaO	0.20	$CaCl_2 \cdot 2H_2O$ (C.P.)	0.655
FeO	0.18	$FeCl_2 \cdot 4H_2O$ (C.P.)	0.606
	100.0%		125.0 gm (86.5 cc)

was sealed, it was heated to the desired equilibrium temperature and held at that temperature for about 40 hours. It was then chilled to room temperature in 1–3 hours by cooling in air. When the bomb was opened there was usually a slight escape of gas, probably partly hydrogen. In some of the experiments, there were three phases seen, an aqueous solution (hereafter called the water solution) standing over a greenish colored viscous liquid (hereafter called the silicate solution) in which crystals were dispersed, more being near the bottom than the top. The three products were separated for study by pouring off the water solution and by washing the silicate solution away from the crystals with hot water. Table 5 records the temperatures and times of heating, and some data on the composition of the three phases. The concentration of the components in the two liquid phases was determined in the case of Experiment 10, and the calculated partition coefficients are shown in Table 6 below.

Liquid immiscibility between silicate and water solutions has also been

TABLE 5.

Exp. No.	Temp. °C	Total weight of charge gm	Degree of filling %	Crystals weight % of product	Water in liquid phases weight %		Solid phases
					Water sol.	Silicate sol.	
P-8	499°±2°	125	75.8	6.4	Leaked during chilling	26.6	n.d.
P-10	464°±2°	125	75.8	9.8	81.4	33.3	Orthoclase
P-11	449°±2°	125	75.8	10.0	79.0	34.0	n.d.
P-12	402°±5°	138	83.8	11.9	75.0	34.8	n.d.
P-13	304°±3°	142	86.2	14.0	60.1	n.d.	n.d.
P-15	277°±4°	142	86.2	n.d.	59.0	—	n.d.
P-15	25°	—	—	n.d.	61.4	—	n.d.

seen in several experiments which have been carried out in this laboratory to determine the conditions of stability of tourmaline. One charge containing the components of tourmaline, with a relatively large amount of boric oxide, was heated at 452° ± 1° C. for 3 days. The result was two liquid phases. The silicate glass contained 25.6 percent water and the water solution, 9.5 percent solute.

TABLE 6.

ANALYSIS OF THE WATER SOLUTION AND SILICATE SOLUTION FROM EXPERIMENT P-10 ABOVE.

Component	Concentration in water solution gm/100 gm	Concentration in silicate solution gm/100 gm	Conc. in water solution / Conc. in silicate solution
SiO_2	7.47	24.8	0.30
Al_2O_3	0.0268	2.32	0.011
B_2O_3, P_2O_5 } by difference	1.44	14.1	0.10
CaO	0.150	0.215	0.70
FeO	0.011	1.06	0.010
Cl	3.40	1.73	2.0
F	1.17	1.25	0.94
Na_2O, K_2O	20.0	22.1	0.95
H_2O	81.4	33.3	2.4

From the data in Table 5, and the results of the work of Goranson (3, 4), a binary phase diagram was drawn which describes qualitatively the deduced phase relations during the cooling of a granite (Fig. 1). Under "silicates" are grouped all of the components which form compounds of the homopolar type,[3] such as SiO_2 and Al_2O_3, and those which form homopolar type crystals with them, such as FeO, MgO, and CaO. Under "salts" are grouped the ionic-homopolar compounds such as K_2O, Na_2O, and Li_2O combined with SiO_2, B_2O_3, P_2O_5, WO_3, SO_3, CO_2, and the ionic compounds such as NaCl, NaF, and Na_2S. Under "water" are grouped all of the components similar to water and soluble in it, such as CO_2, CO, and H_2S. The diagram is only semiquantitative, because it is impossible to represent such a complex system on a plane diagram.

Let us consider the phase changes in a granite magma with a composition as given above, intruded completely in the liquid state but without any super-heat, and crystallizing completely at a depth of 10 kilometers. This condition at the start would be represented at point A on the diagram, which is at 750° C. As the magma cools, anhydrous silicates crystallize and the rest-magma becomes richer in water and other fluxes. At the point B, the water content of the rest-magma has reached its limiting value of approximately 10 percent, and the temperature is approximately 550° C. Further crystallization of silicates brings about the appearance of a new phase con-

[3] The term homopolar (= covalent) is used for the bond type which is more homopolar than ionic, and the term ionic, similarly, for the bond type more ionic than homopolar, it being assumed that all of the transparent compounds (except the weakly bonded molecular crystals) can be placed between these two extremes. The criterion of bond type can be taken as a first approximation to be the solubility of the compound in an ionic liquid, say water or fused NaCl.

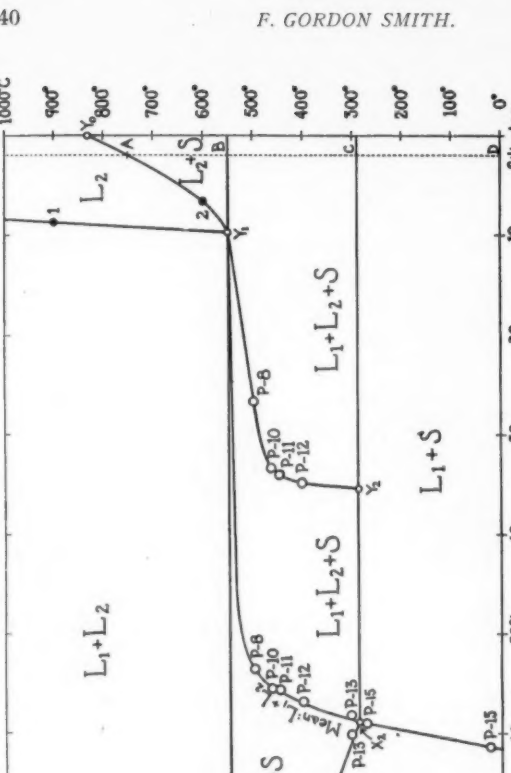

FIG. 1. Approximate phase diagram showing the course of crystallization of a granite magma which contained 2 percent water and 1 percent salt fluxes, under a pressure of 2,500 bars (10 kilometers of rock load). Point 1 was found by interpolation from the 900° isothermal data of Goranson (3) and the slope of the phase boundary through point 1 was taken from the 980 bar isopiestic data from the same work. Point 2 is a value obtained by Goranson (3), and the curve through point 2 was made similar to the albite melting point curve also determined by Goranson (4). The points $X_{1,2}$ and $Y_{0,1,2}$ are terminations of extrapolated curves. The point Y_0 (the melting point of dry granite) is consistent with the data of Greig, Shepherd, and Merwin (6). The other points were determined in the experiments described opposite. The solid lines are phase boundaries, either in the plane of the paper or projections onto the plane of the paper, except the line which represents the average composition of the rest-magma during the pegmatitic stage.

sisting of a water solution of silicates and other magma components, especially those which are more soluble in water than in the silicate liquid. The two liquids are immiscible and remain so until the silicate liquid is entirely used up in forming crystals and more of the water solution. Therefore below point C, at approximately 290° C., only one fluid phase is present. Further cooling of this water solution crystallizes silicates and other compounds, such as quartz and metallic sulphides, down to a very low temperature D. It will be realized that the three-phase condition shown in Figure 1 at 550° C. will not be an invariant point for compositions lying between 10 percent water and 93 percent water, because the composition of the components in solution changes as compounds crystallize. In other words the system is not really binary. This will be of considerable importance after the rarer elements begin to crystallize. Thus the three-phase condition moves to a lower tem-

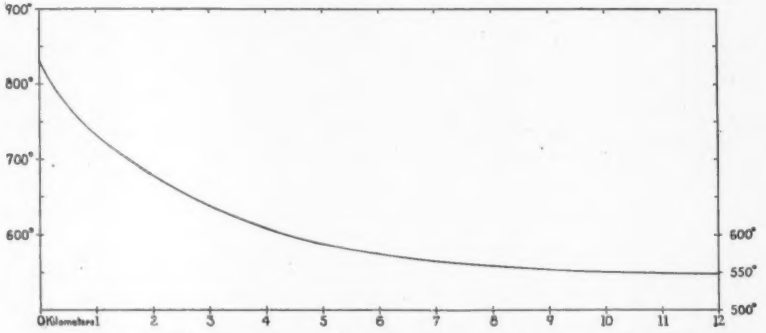

FIG. 2. Approximate upper temperature limit of the pegmatitic stage (two liquids plus crystals) as a function of depth of burial, assuming that the pressure on the magma equals the pressure of the rock load. This curve is based on data published by Goranson (3, 4).

perature and the liquid immiscibility limits also change. This can be visualized as a change of the diagram in a direction perpendicular to the plane of the paper, but projected back on to the plane of the paper. The experiments described above were designed to duplicate the composition after most of the homopolar liquid has disappeared due to crystallization of the common silicates. The upper limit of the three-phase condition was placed at 550° C. to conform with the extrapolation from Goranson's data. This limit is a function of pressure, and the quantitative relation is shown in Figure 2. The lower limit was not determined exactly because it depends upon the estimate of the content of oxides such as B_2O_3 and P_2O_5 in the magma, and a general average would be somewhat difficult to deduce. Provisionally the lower limit is taken to be approximately 290° C. and this is shown in Figure 1.

It might be argued that the composition selected for the test of liquid immiscibility is unique in some way. Since the selection of the fluxes was the most arbitrary part of the composition, a series of experiments was carried

out with a variation of the fluxes from the acid to the alkaline side, but with no change in the general phase relations. The following Table 7 shows the fluxes used in the series, the temperature during the establishment of equilibrium, and the phases observed after chilling. The degree of filling of the bomb was nearly the same in each run. The conclusions reached from this series of experiments were that, other things being constant, the ratio of solids to liquid decreased as the solutions were made more alkaline, and there is only a slight difference in the solubility of homopolar compounds in homopolar liquids when there is a change in the composition of the system which would be equivalent to a change from acid to alkaline if the liquid were ionic.

TABLE 7.

Experiment	P-4	P-6	P-11
Borate	B_2O_3	$K_2O \cdot 2B_2O_3$ (tetra-)	$3K_2O \cdot B_2O_3$ (ortho-)
Phosphate	P_2O_5	$Na_2O \cdot P_2O_5$ (meta-)	$3Na_2O \cdot P_2O_5$ (ortho-)
Chloride	NaCl	NaCl	NaCl
Fluoride	NaF	NaF	NaF
Temperature	450±2° C.	452±3° C.	449±2° C.
Phases	2 Liquids + Solids	2 Liquids + Solids	2 Liquids + Solids
Acidity-Alkalinity of Hydrothermal Solution	Acid	Neutral	Alkaline

If the above sequence of phase changes takes place in deep-seated magmas, from which residual liquid are pegmatite veins formed? If it is postulated that the last remaining silicate liquid is responsible for the pegmatite veins and the immiscible water solution is responsible for the quartz-sulphide veins, then it is necessary to show that certain components such as Al_2O_3, Cb_2O_5, Ta_2O_5, ZrO_2, and TiO_2, which are characteristically present in appreciable amounts in pegmatite veins and almost lacking in quartz-sulphide veins, should be almost completely partitioned into the silicate liquid, and other components such as S and CO_2, which are characteristic of quartz-sulphide veins, should be almost completely partitioned into the water solution. Also, some components such as SiO_2, B_2O_3, P_2O_5, Na_2O, and K_2O which are present in minerals in both types of veins should be present in appreciable amounts in both types of liquids. Representative types of such partitions have been observed in several experiments. The element zirconium is a good example. In a preliminary test of liquid immiscibility (Experiment P-2), which was qualitatively similar to those described above, but with a different content of fluxes, 0.62 percent ZrO_2 was added to the charge. The bomb was kept at a temperature of 440° ± 5° C. for 12 hours, and then chilled. No trace of zirconium could be found in the water solution standing over the glass. Table 6 shows that aluminum also is much more soluble in the silicate liquid than in the water solution. Therefore if liquid immiscibility occurs at a late stage in the cooling of a hydrous magma, it is evident that the pegmatite veins are formed by deposition from the residual silicate liquid part, and not from

the derived water solution. This accounts for the great difference in the chemical composition between pegmatite and quartz-sulphide veins.

An interesting relation exists between the partition coefficients of water and the very ionic salt NaCl. It is unlikely that the near equality of the partition coefficients is a coincidence, but it is more likely that the partition of all ionic components between the more ionic water solution and the more homopolar silicate solution is similar under the same conditions. This is an important generalization, since if we know the solubility of water in the silicate rest-magma, we can calculate the approximate partition of the ionic components between the silicate and hydrothermal rest-magmas. In the calculations we would include ionic salts which have some homopolar properties, such as fluorides which can form fluo-silicate and fluo-aluminate groups, and

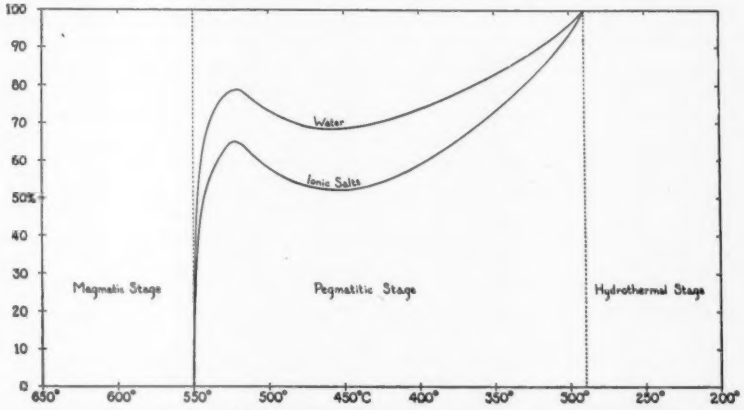

FIG. 3. Percentage of the total water and ionic salts in the magma taken into the hydrothermal solution fraction, as a function of temperature, with other conditions described opposite.

sulphates and carbonates which have a homopolar group in their composition. Therefore the ratio between the partition coefficients of the salts and water would be less than 1, and probably near 0.5. Assuming this relation to be valid over the range of temperature where the two immiscible liquids are present, the fraction of the total ionic salts in the water solution was calculated as a function of temperature, using the interpolated and extrapolated water content of the two liquids shown in Figure 1. The results were plotted graphically in Figure 3. It is evident that considerably more than one half of the total ionic salts enters the water solution soon after its appearance and the remainder is removed from the silicate liquid more slowly as it disappears. This fractionation ratio would be greater or smaller depending upon the bonding properties of the various elements that form ionic salts in magmas, and would be near zero for the amphoteric oxides such as alumina and zirconia.

There is a significant difference in the composition of the two immiscible solutions with respect to the alkaline oxide/acidic oxide ratio.[4] The ratio of weights of $Na_2O + K_2O$ to $Cl + F + B_2O_3 + P_2O_5$ in the water solution of Experiment P-10 is 3.41 : 1, but in the silicate liquid it is only 1.28 : 1. This means that the water solution fraction is more alkaline than the silicate liquid, in direct contradiction of the pneumatolysis hypotheses presented by many theorists that the aqueous fraction evolved by a magma would not only be more acid than the parent liquid, but would actually be acid in the chemical sense.

There is also a great difference in the viscosity of the two immiscible solutions at room temperature, and there is no reason to suspect that the difference would become very much less at elevated temperatures. The viscosity of the silicate liquid was found to vary with temperature very much like soda-lime glass in its softening range, that is, it decreased rapidly with rise in temperature. However, the viscosity of the water solution would also decrease as its density is decreased by an increase in temperature. It was found in a total of 16 experiments in which liquid immiscibility was observed that at room temperature the chilled silicate liquid varied in viscosity between that of common soda-lime glass and soft tar. The viscosity appeared to be highest for compositions high in aluminium, and lowest for composition high in ionic-homopolar fluxes such as alkali borates, phosphates, and tungstates, but also appeared to depend on the ratio of alkali oxide to silica and on the water content. The ratio of viscosities of the two liquids was estimated to be between $10^6 : 1$ and $10^8 : 1$, which would mean that, under a similar driving force, the hydrothermal solution could move 10 kilometers up a fissure, in the time taken for the pegmatitic solution to move only a few centimeters or millimeters. This would explain the separation of the pegmatite and quartz-sulphide veins both in place and time of deposition.

If the above hypothesis of the magmatic phase changes is acceptable, it is proposed that the various stages be given the following designations.

1. magmatic stage (crystals + one fluid phase),
2. pegmatitic stage (crystals + two fluid phases),
3. hydrothermal stage (crystals + one fluid phase).

The magmatic stage could be subdivided into early and late stages, and another stage could be added to cover the possible condition before crystals have started to form (*i.e.* the super-heated stage). The deuteric effects observed in plutonic rocks might be late magmatic, or hydrothermal in origin, and so could not be given a separate stage designation. Pegmatite dikes, especially

[4] A fundamental difficulty with the usual chemical terminology was met with in this and related work on tourmaline. The terms acidic and alkaline refer to aqueous solutions in which the solute is ionized, but have no meaning when the solutions are concentrated or when water is a minor component or lacking. A homopolar liquid cannot be said to be either acidic or alkaline, because hydrogen ions and hydroxyl ions do not occur. We could call a homopolar solution acidic if we find that when it is dissolved in water to a standard concentration the resulting solution has more hydrogen ions than hydroxyl ions, but there is no standard method in use. It is suggested that a standard method might be to dilute the solution such that there is 1 gram of components other than water in 1,000 grams of resultant aqueous solution, at 25° C.

the simple types which are merely coarse grained granite, could be formed in the late magmatic stage as well as later when the magma is in the three-phase, or pegmatitic stage, and therefore could start to crystallize much above the upper limit of the pegmatitic stage.

On the basis of the phase diagram shown in Figure 1 above, an important sequence of events is possible in nature. Say that when the granite was a little below the temperature of point B, most of the water solution of composition near X_1 was removed through fissures, leaving the more viscous liquid of composition near Y_1 in contact with the magmatic crystals. Then, at a lower temperature, a water solution say of composition near X_2 was similarly removed through fissures. The composition of X_1 and X_2 would be very different. The first to be expelled (X_1) would have a much higher concentration of the very ionic components, such as alkali halides, sulphides, sulphates, and carbonates, but the second liquid (X_2) would contain more of the partly homopolar compounds such as alkali silicates, borates, and phosphates. In addition, if a pegmatite dike is formed by injection and crystallization of the Y_2 liquid in fissures, there would be evolved in a similar way a hydrothermal solution from which further silicate minerals would separate down to a low temperature. Therefore two lines of descent of the rest-magma are possible: a hydrothermal lineage, showing a considerable change in composition, but not necessarily a discontinuity, and a pegmatitic lineage, showing a marked discontinuity between the earlier magmatic and the later hydrothermal stage. Because of the accidental nature of fissure filling and concurrent filter pressing of the magma, the two lines of descent might not be resolvable around every batholith. However, this hypothesis might explain the frequently noted two-stage deposition in complex pegmatites, the presence of low temperature minerals such as zeolites in some pegmatites, and the low temperature of formation of some pegmatite minerals as determined recently by Ingerson (8).

CONCLUSIONS.

Near the end of magmatic crystallization there is the generation of a water solution which is immiscible with the residual silicate solution, and soluble components are partitioned between the two liquids. The crystallization of the silicate liquid in channels of escape from the magma forms pegmatite veins, and the crystallization of the water solution in similar channels forms veins containing the metallic sulphides.

ACKNOWLEDGMENT.

The Advisory Committee on Scientific Research of the University of Toronto assisted this work by a grant of money for equipment.

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May 10, 1948.

GROUND-WATER INVESTIGATIONS IN THE UNITED STATES.[1]

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BEFORE discussing ground-water investigations in the United States I should like to outline briefly the broad problems of water supply, water control, and conservation, in the solution of which ground-water investigations play an important part.

For mere existence, a man requires only about 2 quarts of water per day. However, even in simple pastoral or agricultural settings, the biological necessity represents only a part of the total needs for water, and in our own complex industrial and agricultural economy great quantities of water are needed for a multitude of purposes. Water is needed for sanitation, for washing clothes, for facilitating sewage disposal, for scrubbing floors, and for processing foods. It is needed for fire protection, for generating power, and for industrial processes; for irrigation, for air conditioning, and even for producing atomic energy. The task of providing water at the right time and place is a serious problem which fully occupies the attention of thousands of engineers and chemists and a smaller number of geologists. Intimately associated with the water-supply problem is the problem of controlling floods to minimize the erosion of our soils and to conserve flood water for beneficial uses. For obvious reasons, many of our agricultural, industrial, and urban developments have taken place along waterways where they are vulnerable to the ravages of floods which appear to become more costly almost year by year. There is good reason to believe that the demand for water supply will continue to increase and that the demand for control and conservation of flood waters will also increase. Projects for accomplishing these ends will become more expensive and their planning and design will require greater knowledge of our water resources and of the basic geologic and hydrologic factors affecting them.

Especially during the past century, the use of water has increased at an amazing rate. In 1850 only 83 cities in the United States had public water supplies, and only a small proportion of the homes in these cities had water piped directly from the city mains. By 1939 there were 12,760[3] municipal waterworks and thousands of industries had private supplies from wells or surface-water sources. As the number of waterworks increased, the uses of water and the per-capita consumption also increased. The quantities of water used for a few purposes are given below. Flush toilets, bathing and laundry, street cleaning, and fire protection require an average of about 40

[1] Presented at the joint meeting of the Society of Economic Geologists and Geological Society of America, Ottawa, Canada, December 1947.

[2] Geologist in Charge, Ground Water Division, Water Resources Branch, U. S. Geological Survey.

[3] Engineering News-Record, vol. 123, p. 414, 1939.

to 75 gallons per day per capita.[4] Processing a ton of steel in highly finished form requires about 65,000 gallons[5] of water; making a gallon of gasoline takes 7 to 10 gallons[6] of water. Vast quantities of water are used for air conditioning and for making paper, explosives, coke, textiles, and a host of other products. Thus, a large city, such as Chicago, with numerous industries may have a per-capita water consumption as high as 250 to 300 gallons per day.

Only a few thousand acres in the West was irrigated in 1850, but 21 million acres[7] was irrigated in 1939, and many additional irrigation projects are under construction. An acre of cotton uses about 2.5[8] acre-feet, or 800,000 gallons of water, during the growing season; an acre of alfalfa requires about 4 acre-feet of water; irrigation of truck gardens, fruits, sugar cane, rice, and other crops also requires large amounts of water. In eastern United States, supplemental irrigation is increasing because the application of a relatively small amount of water when it is needed by crops may double or triple the yield of the land.

The greatly increased use of water has, in many places, almost fully utilized the readily available water supplies, drawn ground-water levels dangerously low, caused sea water to enter streams and ground-water reservoirs in coastal areas, and permitted oil-well brines or factory wastes to pollute many of our ground-water reservoirs and streams. Thus, the development of additional water supplies for new projects or industries has become increasingly difficult and costly. Nevertheless, it would be a mistake to infer that our water supplies are approaching exhaustion. Actually, much can be done to conserve and thereby increase the total amount of water available for beneficial use. For example, in many places spacing pumped wells over wider areas would prevent excessive lowering of the ground-water levels. Artificial recharge of ground-water reservoirs by spreading flood waters and by other means has been successful in several areas. Abatement of pollution in streams and ground-water reservoirs, retention of flood waters in reservoirs for later use, control of reservoir stages by forecasting normal and flood flows of streams, control of silt and sedimentation, and other measures are being carried out to increase the supply available for perennial beneficial use. The continued growth and prosperity of the nation will depend to a large degree upon the success with which these problems are attacked and solved.

Unlike most mineral resources, water is not exhaustible, in the strict sense, because it is replenished from time to time by precipitation. A surface reservoir may be dangerously low and be refilled in the nick of time by heavy rains. Heavy pumping may cause ground-water levels to decline progressively until pumping is no longer economically feasible, but when pumping is temporarily

[4] Turneaure, F. E., and Russell, H. L., Public water supplies, 4th ed., p. 19, John Wiley & Sons, New York, 1940.

[5] Lloyd, Kenneth M., Industry and water supply in Ohio: Ohio State Univ. Exper. Sta. News, p. 31, April 1946.

[6] Jordan, Harry E., Industrial requirements of water: Am. Water Works Assoc. Jour., vol. 38, pp. 65–68, 1946.

[7] Census Bureau.

[8] National Resources Committee, Regional Planning, pt. 6, p. 91, 1938.

or permanently reduced the water levels usually recover. Likewise, a period of heavy rainfall following a drought period may induce recharge sufficient to restore water levels essentially to predrought levels.

Only a part of the water taken from streams or pumped from wells is actually consumed. In many manufacturing processes water is merely a washing agent and is essentially unreduced in volume by its use. Water used in boilers or in quenching hot metal is partly evaporated, but the remainder is discharged or re-used. Water used in irrigation is partly evaporated and partly transpired by plants, but there is always an excess which is discharged and which carries away undesirable salts. The excess water from all these uses returns to the stream or to the ground altered by the concentration of minerals contained in it, or by the addition of dissolved constituents, or of color, or sediment, or simply by the addition of heat. It may be re-used for the same or other purposes with or without the addition of new water. For example, the water of the Pecos River, in Texas and New Mexico, is used and re-used for irrigation and domestic supply seven or eight times between its source and Girvin, Texas. Although water is added from tributary areas along its course, each time the water from the river is used the mineral concentration increases, and a few miles above Girvin it is so highly mineralized that even the most resistant crops are unable to survive its application. Even so, it may still have potential use, because water also possesses the energy of position and in its journey from the mountains to the sea it may be used many times over for generating hydroelectric power.

Another characteristic peculiar to water results largely from the vagaries of precipitation. Many places are faced successively with water shortages and destructive floods. Although enormous sums have been spent on flood control, complete protection from floods is difficult and often prohibitively costly, and in only a few places has it been accomplished.

Whatever conclusions are reached with regard to the economics of flood control by storage reservoirs, from the standpoint of conservation of water supply it is advantageous to salvage as much of the flood water as possible. In certain areas where water supply is now inadequate, as it is in many places west of the 100th meridian, much of the water from precipitation escapes to the sea during floods. In Los Angeles County, Calif., much of the flood water is retained in surface reservoirs from which it is later discharged into specially prepared recharge basins and seeps into the under-ground aquifers. Some of the flood water is caught in seepage reservoirs designed to promote infiltration into the ground-water basins, and some of it escapes to the sea, but essentially all the flood water in the Los Angeles area will be put to beneficial use when the projects now under consideration are completed. Plans for similar flood control in other parts of the country are in various stages of execution.

Ground water and surface water are so intimately related that for proper solution of the over-all problems of water supply, control, and conservation it is now necessary to have all the facts regarding both. Precipitation, which is the source of both, is partly lost, largely through evaporation. Especially during the growing season, a large part enters the ground and is transpired by

plants. The remainder percolates downward below the plant roots to become ground water, or runs off directly as surface flow. The ground water, returning to the surface as seeps or springs, provides the base flow of the streams which prevails through periods of low precipitation. On the other hand, especially in the West, many streams lose water by seepage in certain stretches and thus recharge the ground-water reservoirs.

Many of the basic ground-water investigations in the United States are carried on cooperatively by the U. S. Geological Survey and State or local agencies, including State Geological Surveys, State Engineers, counties and municipalities. In Illinois ground-water investigations are made by the State Geological Survey and the State Water Survey; and in Missouri investigations are made by the State Geological Survey. In California a large staff of engineers in the State Division of Water Resources for many years has been investigating overdraft of ground-water supplies. Recently arrangements were made whereby the U. S. Geological Survey, in addition to its investigations in Los Angeles, Orange, and Santa Barbara Counties, will assist the Division of Water Resources in the geological phases of a State-wide inventory of the water resources of California. Various other Federal and State agencies are obtaining some data on ground water in connection with special phases of their work.

The ground-water investigations of the U. S. Geological Survey began more than 50 years ago. At that time ground-water supplies were little developed. Consequently, most of the early field investigations were of the exploratory type. Laboratory and field studies by King, Slichter, and later by Meinzer outlined the broad principles of ground-water occurrence and movement. However, before the deep-well turbine pump was developed in the early part of this century, use of ground water in large quantities was limited to areas of springs or artesian flow, or to areas where the water level was within reach of suction pumps. After the turbine pump was introduced, it became possible to pump economically even where water levels are deep; power costs also decreased, and well drilling and finishing methods were improved to increase the efficiency of wells. Because of these advances, ground water came to be used in ever-increasing quantities, first in areas where surface water was not readily available, and later in areas where ground-water supplies were more economical because they obviated the long pipelines, collection works, and costly treating plants needed for surface-water supplies. The first great expansion of ground-water supplies was made largely without technical guidance. Because of their immense storage capacity, the ground-water reservoirs were regarded as inexhaustible, and in many places development was well advanced before progressively declining water levels brought about the realization that ground-water reservoirs may be depleted. As a result, demands for detailed ground-water studies steadily increased. These studies are thorough, systematic investigations which include areal geologic mapping; subsurface studies occasionally augmented by geophysical surveys and test drilling to determine the structure, thickness, and the sequence of water-bearing and non-water-bearing beds; collecting data on fluctuations of water levels in relation to precipitation and to pumpage;

determining the recharge and perennial yield; inventories of ground-water withdrawal; test pumping to determine coefficients of permeability, transmissibility, and storage; determining the quality and temperature relationships, and the relations between surface and ground water. The work does not include supervision, construction, or control of water supplies.

The U. S. Geological Survey is now making cooperative ground-water investigations in 42 States and in Alaska, Hawaii, the Virgin Islands, and Puerto Rico. In general, the State or local authorities are most familiar with the needs in their States, and they are largely responsible for designating the areas in which investigations are to be made. Most of the ground-water staff of the U. S. Geological Survey now have headquarters in field offices, of which there are about forty.

In addition to the cooperative investigations with States and local agencies, certain investigations primarily of Federal interest are being carried out with use of Federal funds only. For example, an extensive program of ground-water investigations is being conducted in the Missouri River Basin to provide basic information needed for planning and constructing the various water projects that are authorized or planned. This information will include determination of existing ground-water conditions and probable effect of irrigation on ground-water levels, especially with reference to waterlogging and drainage, canal locations with reference to seepage, areas where irrigation with ground water is feasible, the location of potential sources for farmstead and municipal water supplies, and so on. Other investigations, such as that recently started in the Central Valley of California, will provide basic information needed in the project to use excess flood waters for recharging the heavily pumped ground-water reservoirs in the San Joaquin portion of the valley. Several projects also are under way in connection with defense plans.

A large program of measurement of ground-water levels in observation wells has long been an integral part of the cooperative program. Recently a small Federal fund was provided for extending this program, analyzing the data, and determining the current status of our ground-water supplies on a Nation-wide scale. The program includes the investigation of the possibilities of forecasting low-stage stream flows from fluctuations of ground-water levels, enabling more efficient control of reservoir and river stages in the operation of hydroelectric plants and permitting considerable economies in the generation of power. Conversely, base flow is an index of ground-water storage. As the ability of the ground-water reservoirs to absorb water materially affects the runoff to be expected from rainfall, the analysis of data on ground-water levels should aid in flood forecasting.

In addition to and as part of the above program, several research projects are under way, including the study of movement of water through soils and water-bearing materials; infiltration from streams and its effect on the temperature and quality of the ground water; the occurrence of ground water in fractures and solutional openings in impermeable rocks, such as limestone, sandstone, granite, etc., and the improvement of our techniques for locating producing wells in such rocks; earth subsidence resulting from the withdrawal

of ground water, and related problems connected with elasticity and compressibility of artesian aquifers; methods of analyzing results of pumping tests to determine coefficients of transmissibility and storage; and a number of other projects.

With respect to the probable future of ground-water investigations, it should be pointed out that ground-water development was expanding rapidly in the middle thirties. In 1935 the total use of ground water in the United States amounted to about 10 billion gallons a day. The development was greatly accelerated by the needs of the war, so that by 1945 the total pumpage had nearly doubled[9]. Although the war ended more than 2 years ago there has been no sign of a decrease in the use of ground water. In fact, both surface water and ground water are now being used in greater quantities than ever before. As the use of water approaches ever more closely the limits of the available supply, it is believed that water-resources investigations will be needed with ever-increasing urgency because water constitutes the prime factor in the continued development of the Nation's industrial and agricultural economy.

U. S. GEOLOGICAL SURVEY,
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TITANIC IRON ORE FORMED BY DISSOCIATION OF SILICATES IN GRANULITE FACIES.

HANS RAMBERG.

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ABSTRACT.

Rocks of charnockitic affinity—including anorthosites—are recrystallized under granulite facies conditions. It is shown that the stability relationships of some silicates (hornblende, biotite, sphene, and titanic augite) require a liberation of Ti and usually Fe from the silicate lattices under granulite facies conditions. Because titanic iron ore appears to develop in rock complexes recrystallized in granulite facies, it is suggested that there are some crucial genetic relationships between the liberation of ore elements from the silicates and the segregation of ore bodies in, or near, basic noritic rocks and anorthosites.

We have reason to believe that the liberated titanium and iron diffuse in the form of atoms, ions, or molecules through the recrystallizing rock complexes and that structural and chemical heterogeneities determine where the ore minerals will consolidate.

INTRODUCTION.

In a paper in press (34) [1] the writer has shown that a series of rocks ranging from norites through enderbites and mangerites toward charnockites received its typical mineralogical character during recrystallization at P,T-conditions corresponding to granulite facies (16). The investigated complex of rocks covers a 150 km wide zone in a Precambrian folded chain between Holsteinsborg and Egedesminde in West-Greenland. To the north and south of the high grade rocks, gneisses occur belonging to amphibolite- and epidote-amphibolite facies (Fig. 1). The vast area of granulite facies rocks is to be considered a high grade variety of "common" heterogeneous hornblende- and biotite-bearing gneisses.[2]

[1] Numbers in parentheses refer to bibliography at end of paper.

[2] The study of this area is a part of the systematic geological surveying of the Precambrian of Greenland recently started by the Geological Survey of Greenland, Copenhagen.

The rocks in the high grade area are mineralogically and structurally identical to the anorthosite-charnockite series described from different parts of the world, [India (24); Norway (5, 6, 13, 27, 28); Ceylon (1); Africa (20, 18); Ellesmereland (12); U. S. A. and Canada (2, 11, 39)].

The vast massifs of anorthosite, however, so typically connected with some charnockitic provinces, do not occur in the hitherto mapped part of Greenland. In this respect the Greenlandic complex is similar to the classic Indian area, the complex in Uganda, Africa, the rocks of charnockitic affinity in Ceylon, and similar rocks in the Kongsberg-Bamble formation in South Norway. In

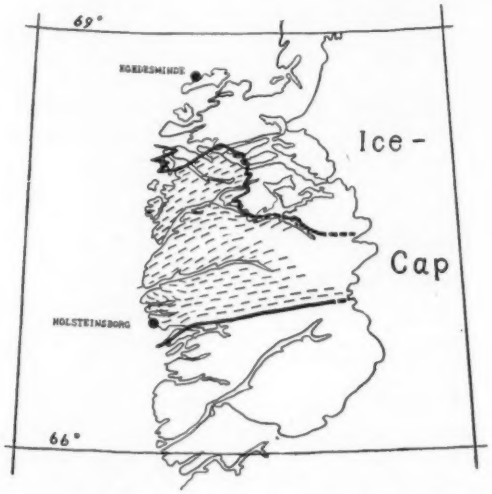

FIG. 1. Sketch map showing position, shape, and mean strike of the granulite facies area between Holsteinsborg and Egedesminde in West-Greenland.

West-Greenland the main rock is a hypersthene-bearing quartz diorite (enderbite, (36)) which partly is massive, partly distinctly gneissic. In this vast complex of enderbitic gneisses, basic noritic rocks and a few occurrences of hypersthene granite are encountered.

Thus, though anorthosite is frequently found in complexes of charnockitic affinity, anorthosite does not appear to be a necessary member of the series. On the other hand, when anorthosite occurs it apparently finds its place, in almost every case, among rocks of charnockitic affinity.

The evidence for the Greenlandic norite-enderbite-charnockite rocks being metamorphic is discussed in some detail in the above mentioned paper in press. This paper deals with the stability relationships of the several minerals—particularly the distribution of some exchangeable elements (Fe, Mg, Ti, Mn) among the ferromagnesian minerals—and proves conclusively that the basic rocks, the intermediate, and most acid rocks exhibit parageneses corresponding

to very nearly the same P,T-conditions. Even the cross-cutting and conformable pegmatites possess parageneses corresponding to the P,T-conditions which prevailed during the formation and recrystallization of the gneissic and massive country rocks. Thus the field and laboratory investigations of the Greenlandic rocks of charnockitic affinity conform to the explanation of the origin of similar rocks in Uganda given by A. W. Groves fourteen years ago.

To me it seems evident that most other charnockitic provinces have, in large part, a similar origin (37). These rocks cannot be interpreted as primary magmatic, because magmatic differentiation requires a gradual decrease of temperature as more and more acid rocks crystallize from the magma. The different members of the series must have received their typical consanguineous mineralogical character during regional metamorphism corresponding to granulite facies. That is so because the mineral species and associations of the several rocks belonging to the norite-anorthosite-enderbite-charnockite series from all parts of the world correspond to very nearly the same P,T-conditions, independent of the bulk chemical composition of the several rocks and pegmatites. To me it seems evident also that the structure of anorthosite-charnockite complexes, as described by R. Balk (2, 3), show that the rocks are intensively recrystallized and mechanically deformed with the help of micro- and macro-creep in their solid state. (With reference to crystalline plasticity and the concepts of micro- and macro-creep see W. G. Burger's chapter in R. Houwink (25)).

Thereby is not the intricate problem of the emplacement of the rock-forming substances in such provinces solved? To what extent is the bulk chemical composition of the several rocks pre-metamorphic, to what extent syn-metamorphic, or perhaps post-metamorphic?

In the Greenlandic area, for example, it is evident that the heterogeneity of the complex, and the chemical composition of the different rocks are to a great extent pre-metamorphic. Alternating layers of limestone, aluminous sediments, sandstones, and layers of mud have given rise to marbles, kinzigites,[3] khondalites,[4] quartzites, and graphite-pyrite-bearing gneisses in the intensively metamorphosed complex. Likewise, a major part of the layers, boudins, and agmatitic inclusions of noritic affinity in the enderbitic gneiss can be followed backward into common diabase dikes cutting through old gneisses belonging to an earlier period of orogeny.

On the other hand, it is evident that a syn-metamorphic rearrangement of rock-forming matter has taken place, partly by mechanical intermingling of solid rocks with different crystalline plasticity, partly by means of interdiffusion of individual atoms, molecules, and ions among the several rocks. Because the metamorphism took place below the stability field of any silicate melt, however, no substances could have been transported in the form of silicate magmas.

One of the best proofs of metamorphic diffusion of activated molecular particles through solid rocks is limestone which to some extent is altered to silicate skarn rock. In this case it can be shown that Si, Al, Na, and often Fe

[3] The kinzigites contain cordierite and garnet in addition to quartz and feldspars.
[4] The khondalites are rich in sillimanite and garnet, but have no cordierite.

and Ti migrated into the altered marble while Ca and CO_2 diffused in the opposite direction.

Also the several syn- and late-metamorphic pegmatites must have originated with the help of diffusion of elementary particles through the country rocks and along the cross-cutting fissures which now are filled with pegmatitic material. That is so because pegmatitic hydrous magmas were unable to form at the P,T-conditions which prevailed during the metamorphic rearrangement of the Greenlandic complex. (This is discussed more thoroughly elsewhere (34)).

Garnet porphyroblasts of diameter up to 10–15 cm in the metamorphic noritic layers are also proof of a quite extended migration of elements in the crystalline rocks. The formation of reaction zones in amphibolitic inclusions and remnants in the enderbitic gneiss also requires a certain sub-solidus mobility of the mineral constituents (Figs. 3, 4, 5).

THE RELATIONSHIPS BETWEEN TITANIC IRON ORE AND SILICATE ROCKS IN GRANULITE FACIES.

The relationship in space and time between the basic members of the rocks discussed above and titanic iron ore was recognized long ago (38), and is now perhaps one of the best examples of consanguinity between silicate rocks and ore.

Commercial titanic iron ore has been encountered only in anorthosites and basic rocks of noritic affinity (9, 29, 15). In anorthosite-charnockite provinces, however, it is evident that ilmenite and titanic magnetite are also minor but typical constituents of the acid members of the rock series. In West-Greenland, for example, ilmenite is a typical minor constituent of the enderbites as well as the charnockites. In some pegmatites in the same area ilmenite is considerably concentrated. Furthermore, at some places in the enderbitic gneiss one finds bands and lenses of an ilmenite-quartz rock.

Because charnockitic provinces now must be considered of metamorphic origin (20, 37, 34), the question arises whether the formation of titanic iron ore in such provinces is pre-metamorphic, syn-metamorphic, or post-metamorphic.

If the ore be pre- or post-metamorphic it might have formed by magmatic differentiation (38, 31) or by hydrothermal solutions and replacement (19). Because recent ilmenite-rich sediments occur at several places (8), it might be tentatively suggested that the ore in charnockitic rocks is highly metamorphosed sedimentary titanic ore.

A pre- or post-metamorphic formation of the ore implies that the titanic iron ore in hypersthene-bearing rocks and anorthosites in granulite facies has no genetic relationship to the recrystallization processes which give rise to the typical character of the silicate rocks. In this case, therefore, one should expect to find ilmenite ore equally often in lower facies, viz. in amphibolite facies, in epidote-amphibolite facies, or in green-schist facies (16). This is not so; segregations of ilmenite ore occur almost solely in granulite facies, and generally in connection with basic rocks and anorthosites. It therefore may be

assumed that segregation of the ore has some genetic relationship to the recrystallization processes which form the several hypersthene-bearing rocks in granulite facies. To establish such a view it is necessary to explain more thoroughly the steps of the ore-forming process.

First, it must be possible to detect the sources of the titaniferous ore. Second, one should be able to show that forces were in operation tending to drive the ore-forming elements from their sources toward the places where the ore is concentrated. Third, it should also be shown that the diffusion currents were powerful enough to transport the quantity of ore elements required.

The first requirement is not related to the complicated kinetic of the metamorphic migration of elements and should be rather easy to satisfy, provided, of course, that the ore actually is of metamorphic-metasomatic origin.

If titanic iron ore is formed by metamorphic-metasomatic processes it is reasonable to suppose that some mineral interactions which take place at the P,T-conditions of granulite facies, in which the ore is situated, will liberate titanium and iron, thus serving as the source of the ore-forming elements.

Such a liberation of titanium and iron is actually connected with some of the most important mineral transitions which take place when certain rocks are exposed to the physical conditions of granulite-facies. One of these reactions is the splitting up of hornblende into plagioclase and rhombic and monoclinic pyroxenes. Another reaction is the transition of biotite into garnet and potash felspar, and a third is the alteration of sphene which is absorbed in lime silicates under liberation of titanium.

Because the comparatively low-metamorphic minerals (hornblende, biotite, and sphene) are richer in titanium and iron than the high-metamorphic minerals, titanium—and in most cases also iron—will be liberated from the silicate lattices when rocks carrying hornblende, biotite, and sphene are metamorphosed in granulite facies.

THE STABILITY CONDITIONS OF HORNBLENDE.

Hornblendes in granulite facies and adjacent parts of amphibolite facies are rich in titanium and iron as shown in Table I. In addition to the few analytical data available it should be remembered that the optical properties of hornblendes occurring in norites, anorthosites, charnockites, etc. are characteristic. The pleocroism is brownish green, the birefringence is rather high, and the extinction angle is small. These properties indicate considerable amounts of TiO_2 (and Fe_2O_3) in the hornblendes.[5]

At rising temperature and pressure through amphibolite facies hornblende absorbs gradually more titanium from the surrounding minerals, so that in granulite facies hornblendes may contain up to 4 to 5 percent of TiO_2. At these high P,T-values, however, hornblende becomes unstable if associated with quartz. The following reactions take place:

[5] The relationship between optical properties and chemical composition of hornblendes from granulite facies will be published at a later date.

(1) $\underset{\text{hornblende}}{NaCa_2(Mg,Fe)_4Al_3Si_6O_{22}(OH)_2} + \underset{\text{garnet}}{(Mg,Fe)_3Al_2Si_3O_{12}} + 5SiO_2 \rightleftarrows$

$$\underset{\text{plagioclase}}{NaCa_2Al_5Si_7O_{24}} + 7\underset{\text{hypersthene}}{(Mg,Fe)SiO_3} + H_2O$$

(2) $\underset{\text{hornblende}}{NaCa_2(Mg,Fe)_4Al_3Si_6O_{22}(OH)_2} + 4SiO_2 \rightleftarrows$

$$\underset{\text{plagioclase}}{NaCaAl_3Si_5O_{16}} + 3\underset{\text{hypersthene}}{(Mg,Fe)SiO_3} + \underset{\text{diopside}}{Ca(Mg,Fe)Si_2O_6} + H_2O$$

(3) $\underset{\text{hornblende}}{NaCa_2(Mg,Fe)_4Al_3Si_6O_{22}(OH)_2} + \underset{\text{biotite}}{K(Mg,Fe)_3AlSi_3O_{10}(OH)_2} + 7SiO_2 \rightleftarrows$

$$\underset{\text{plagioclase}}{NaCaAl_3Si_5O_{16}} + \underset{\text{diopside}}{Ca(Mg,Fe)Si_2O_6} + \underset{\text{orthoclase}}{KAlSi_3O_8} + 6\underset{\text{hypersthene}}{(Mg,Fe)SiO_3}$$

These reactions are complicated, yet it is clear that Ti and Fe in most cases will be liberated on the right hand side of the equations. Table 1 shows that rhombic and monoclinic pyroxenes formed after hornblende, or being in equilibrium with hornblende in granulite facies they are poorer in Ti than the hornblende itself. It is also evident that biotite is richer in titanium and iron than the co-existing hypersthene and diopside (Table II) so that in equation (3) biotite also contributes to the liberation of iron and titanium.

In addition to the data that can be computed from the stability relationships of hornblende, biotite, garnet, and pyroxenes, and the chemical compositions of these minerals, we have definite field evidence for the libration of Ti and Fe in reactions (1), (2), and (3) (see below).

Reactions (1), (2), and (3) are by no means fixed to a certain line in the P,T-field. The position of the transition line in a P,T-field depends on the ratio between the exchangeable elements; Na/Ca, Mg/Fe··/Fe···/Mn/Ti,

TABLE I.

WEIGHT PERCENTAGE OF TiO_2 IN SOME FERROMAGNESIAN MINERALS FROM GRANULITE FACIES.

	Greenland						Uganda					Adirondack			Finland		
Sample No.....	2038	330	37218	Hbg.	37811	37935	G. 74	G. 80	S. 22	S. 347	S. 343	21. L	22. L	31. L	1	2	3
Hornblende....	4.2–	2.51	2.48	2.58	0.37	1.84	—	—	—	3.88	3.37	—	—	—	0.48	2.00	0.4–
Hypersthene...	—	0.11	0.37	—	—	—	0.03	0.07	1.10	—	—	0.07	—	—	0.09	—	trace
Diopside.....	—	—	0.38	—	—	—	—	—	0.7	1.6	—	—	0.59	0.20	—	—	—

The samples from Greenland were analyzed by B. Bruun, University of Chicago.
The data from Uganda are taken from A. W. Groves, 1935.
The data from the Adirondacks are taken from A. F. Buddington, 1939.
Finland 1 is from E. Mikkola and Th. G. Sahama, 1936. Finland 2 ,which belongs to the amphibolite facies, is from Th. G. Sahama, 1948. Finland 3 is from A. Hietanen, 1947, pp. 1036–37.
Hornblende no. 37218 has about 0.1 percent V_2O_5 according to O. Joensuu.

and partly also Al/Si. Rising Ca/Na ratio in the paragenesis, and thus formation of more basic plagioclase, will displace the reactions above toward the hornblende side. Thus hornblende is stabilized at gradually higher temperature (pressure) the more basic the plagioclase.

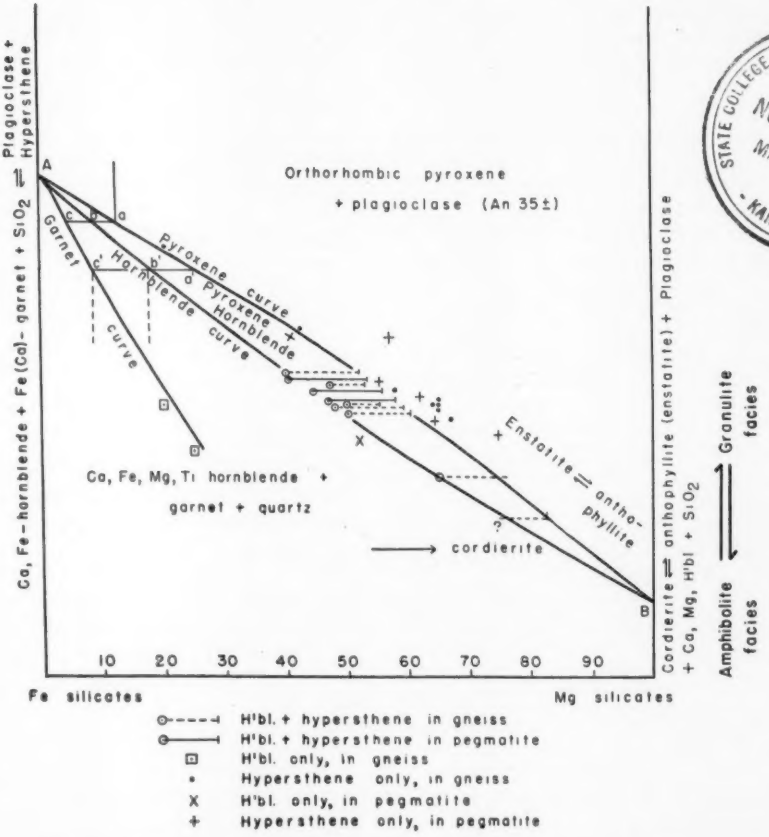

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FIG. 2. Equilibrium diagram of a silicate system corresponding to equation (1). Left side corresponds to pure Fe-members in the system, right side, to pure Mg-silicates. Thus the Pyroxene, Hornblende and Garnet curves give the Fe/Mg ratio of the corresponding minerals when they are in mutual equilibrium. Some minerals and associations from the granulite facies area in Greenland are plotted in the diagram. Note that rhombic pyroxene has a greater Mg/Fe ratio than the co-existing hornblende and garnet. The P,T-difference between points A and B in the diagram is small as compared with the P,T-difference between, for instance, green-schist facies and amphibolite facies.

It is empirically found that, provided the system is not too rich in magnesium relative to iron, the minerals on the low P,T-side of equations (1), (2) and (3) have greater Fe/Mg ratios than the pyroxenes on the high P,T-side (34). That is, the Mg-members in the reactions above react at somewhat lower degrees of metamorphism than do the Fe-members. Thus, at P,T-values situated between the transition line of the pure Fe-members and Mg-members respectively, the several minerals occurring on either sides of equations (1), (2), and (3) can exist in stable equilibrium (Fig. 2). Furthermore, as far as a given P,T-combination is considered, there must be definite Fe/Mg ratios in the hornblende and the co-existing pyroxenes, provided that stability exists and the co-existing plagioclase has a given composition. In addition, if the Fe/Mg ratio in the hornblendes or pyroxenes exceeds those which correspond to equilibrium at the given P,T-values, pyroxene will disappear because the equations (1), (2), and (3) are displaced completely toward the hornblende side. On the other hand, less Fe/Mg ratios make hornblende disappear by reason of the opposite reaction.

In complete harmony with these considerations we find that inside the granulite facies area in West-Greenland the Fe/Mg ratios in the co-existing hornblendes and rhombic pyroxenes in quartzose rocks are about 50/50 and 40/50 respectively when the composition of the plagioclase present is about An_{35}. That is, hornblendes with Fe/Mg ratio equal to, and greater than 50/50 do not react with biotite or garnet during formation of hypersthene, monoclinic pyroxene, and plagioclase in quartzose rocks containing plagioclase more basic than about An_{30-35}.[6]

Thus, under the granulite facies conditions in West-Greenland hornblendes transform into hypersthene and monoclinic pyroxene in quartzose rocks for two reasons: (1) The plagioclase is more acid than about An_{30}. In this case even hornblendes very rich in Fe are altered. (2) The hornblende has less Fe/Mg ratio than about 50/50.

In both cases only a limited amount of the titanium and ferric iron in the unstable hornblende and biotite can be absorbed in the newly formed rhombic and monoclinic pyroxenes. In most cases the pyroxenes are also unable to absorb the total amount of $Fe^{\cdot}$ from the unstable hornblende, biotite, and garnet in equations (1), (2), and (3). The superfluous atoms of Ti and Fe will partly separate as titanic iron ore and partly migrate away from the place of reaction.

The discussion above refers to quartzose rocks at those P,T-conditions which prevailed during the recrystallization of the granulite facies area in West-Greenland. In undersaturated rocks hornblende will be stable at higher P,T-values. In the area in question the P,T-conditions were the same in the acid and in the undersaturated basic rocks, so that in this area it cannot be directly shown that hornblendes are formed at higher P,T-conditions in basic rocks than in acid rocks. Indirectly, however, one can prove that this actually is the case. In the quartz-bearing rocks hornblendes with greater

[6] The conclusion stated here is based on optical and chemical investigation of a number of hornblende parageneses from West-Greenland. As to the detailed discussion the reader is again referred to my paper in press.

(Fe,Ti)/Mg ratios than about 50/50 are stable, whereas hornblendes having a (Fe,Ti)/Mg ratio less than about 40/60 or 50/50 split up into hypersthene and plagioclase. In the basic rocks we often find hornblendes with (Fe,Ti)/Mg-ratio much less than 40/50. Analyses show that some of the hornblendes in the undersaturated rocks in West-Greenland have (Fe,Ti)/Mg ratios equal to 23/77 and even less. That is, in undersaturated rocks in granulite facies even Mg-rich hornblendes can exist in stable equilibrium with the surrounding minerals. When thus the P,T-conditions increase, the Mg-rich component of the hornblende begins to react according to equation (4). At a certain P,T-value a hornblende with a (Fe,Ti)/Mg-ratio equal to 50/50 will be stabilized. It is clear then, that the P,T-value which stabilizes a hornblende with a (Fe,Ti)/Mg-ratio equal to 50/50 in basic rocks must be greater than the P,T-values stabilizing the same hornblende in quartzose rocks.

The reason hornblende is stable at higher P,T-conditions in undersaturated rocks than in quartzose rocks is that reaction (4) takes place at a higher degree of metamorphism than reactions (1) to (3).

(4) $2\underset{\text{hornblende}}{NaCa_2(Mg,Fe)_4Al_3Si_6O_{22}(OH)_2} + 6\underset{\text{hypersthene}}{(Mg,Fe)SiO_3}$

$$+ 2\underset{\text{garnet}}{(Mg,Fe)_3Al_2Si_3O_{12}} \rightleftarrows 2\underset{\text{plagioclase}}{NaCa_2Al_5Si_7O_{24}} + 10\underset{\text{olivine}}{(Mg,Fe)_2SiO_4} + 2H_2O$$

Although hornblendes rich in Mg but poor in Fe and Ti are actually stable in undersaturated rocks in granulite facies, it is empirically found that the hornblendes in such rocks generally have great (Fe,Ti)/Mg ratios (34). That is so because the mean (Fe,Ti)/Mg ratio in these rocks usually is high.

In conclusion we can state: Only aluminous hornblendes with (Fe,Ti)/Mg ratios above a certain critical value are stable in association with quartz and plagioclase of a given composition (say, An_{35}) in granulite facies. The more acid the plagioclase, the greater the (Fe,Ti)/Mg ratio in the stable hornblende.

The (Fe,Ti)/Mg ratio necessary to keep hornblende stable in quartzose plagioclase-bearing rocks in granulite facies is high (about 50/50); hence, most hornblendes in quartzose rocks will split up according to equations (1), (2), and (3) when the rocks are metamorphosed in granulite facies. In quartz-free rocks in granulite facies, hornblendes with low (Fe,Ti)/Mg ratios are also stable. If these basic rocks are subjected to Si- and Na metasomatism, however, the hornblende, if not too rich in iron, will react as shown in equations (1), (2), and (3).

In both cases titanium and iron will be liberated from the silicate lattices so that these elements can form ore minerals "in situ" or migrate throughout the rock complexes.

Field evidence supports this process. Thus, around the numerous amphibolitic inclusions and layers in the enderbitic gneiss in West-Greenland, a reaction zone of hypersthene, ilmenite with inclusions of magnetite, plagioclase, and quartz is present in almost every case. It is important to note that in most cases the concentration of ore minerals in the reaction zone is consider-

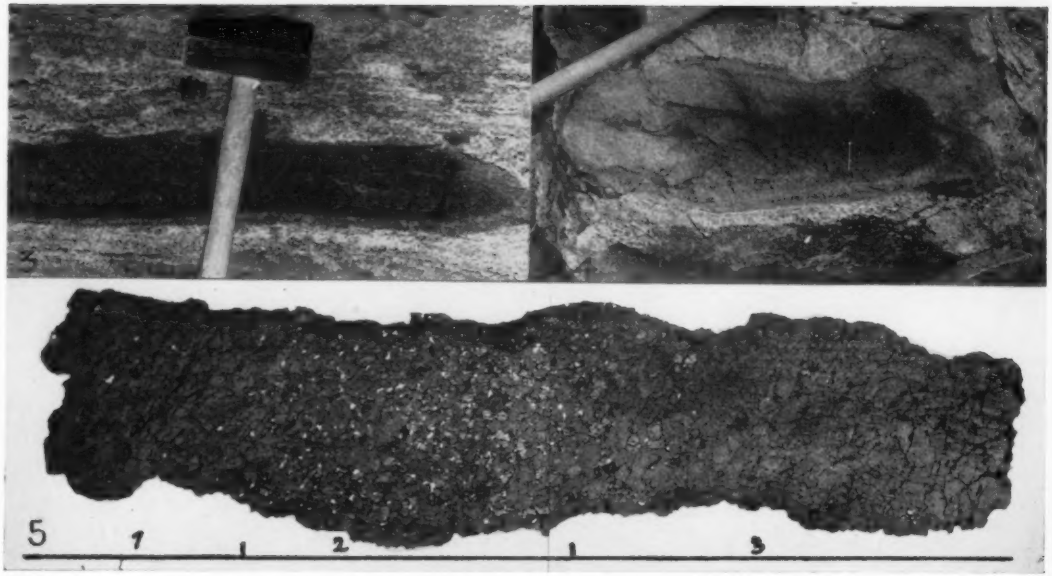

FIG. 3. Amphibolitic inclusion with internal reaction zone of hypersthene, plagioclase, and grains of titanic iron ore occurring in enderbitic gneiss, Nagssugtoq. Photo by H. Ramberg, July 7, 1947.

FIG. 4. Basic inclusion in quartzose garnet-bearing gneiss (granulite). The amphibolitic inclusion is almost thoroughly hypersthenized; only the core contains unaltered dark titaniferous hornblende. Loc., Isortoq, photo by H. Ramberg, July 6, 1947.

FIG. 5. Polished section of a reaction zone similar to Figure 3. Zone 1 is the unaltered amphibolitic inclusion, zone 2 the reaction zone, and zone 3 is the enclosing enderbitic gneiss. The white spots in zone 2 are grains of ilmenite (and magnetite) formed under the hypersthenization of the titaniferous hornblende. Zone 2 is about 2 cm broad. Loc., Holsteinsborg, photo by Chr. Halkier, Copenhagen.

ably greater than in the surrounding enderbitic gneiss, and much greater than in the less altered amphibolite (Figs. 3, 4, and 5).

THE STABILITY CONDITIONS OF BIOTITE.

Reaction (3) shows that biotite in association with hornblende becomes unstable in granulite facies. In this case the superfluous content of TiO_2 in the altered biotite contributes to the formation of titanic iron ore.

In Ca-poor rocks such as the kinzigitic and khondalitic gneisses the instability of biotite is shown by its transformation into garnet according to the following reactions:

(5) $\underset{\text{biotite}}{K(Mg,Fe)_3AlSi_3O_{10}(OH)_2} + 3SiO_2 \rightleftarrows \underset{\substack{\text{potash}\\\text{felspar}}}{KAlSi_3O_8} + 3\underset{\text{hypersthene}}{(Mg,Fe)SiO_3} + H_2O$

(6) $\underset{\text{biotite}}{K(Mg,Fe)_3AlSi_3O_{10}(OH)_2} + \underset{\text{sillimanite}}{Al_2SiO_5} + 2SiO_2 \rightleftarrows$

$$\underset{\substack{\text{potash}\\\text{felspar}}}{KAlSi_3O_8} + \underset{\text{garnet}}{(Mg,Fe)_3Al_2Si_3O_{12}} + H_2O$$

Because garnet is richer in iron than the co-existing biotite (34), no iron will be liberated when the reactions above go to the right. Garnet, however,

TABLE II.

TITANIUM IN BIOTITES.

	Greenland				Uganda	Dartmoor granites					Mean of 59 anal.
Sample No.	343	325	330	338	G. 80	63	64	65	66	67	
TiO_2%	5.25	6.05	5.43	5.90	1.42	2.66	1.77	2.05	3.51	1.39	3.34

Greenland: analyst, B. Bruun. Uganda: see ref. Table I. Dartmoor: A. Brammall and H. F. Harwood, 1932. The mean of 59 anal. is from A. H. Hall, 1941.

TABLE III.

TITANIUM IN GARNETS FROM GRANULITE FACIES AND ADJACENT PARTS OF AMPHIBOLITE FACIES.

	Greenland				Uganda	Finland		Dart-moor	Adiron-dack	Great Slave Lake
Sample No.	37847	37218	Isortoq X, Y, Z	325	G. 79	1	2	68	23L	
TiO_2%	trace	trace	trace	0.05	0.21	0.19	0.24	none	none	0.03

68: A. Brammall, etc., 1932. Finland: A. Hietanen, 1943, p. 15. G. 79: A. W. Groves, 1935, p. 160. 23L: A. F. Buddington, 1939, p. 32. Great Slave Lake: R. F. Folinsbee, 1941, p. 50. Greenland: analyst, B. Bruun.

is unable to absorb the content of titanium in most biotites, so that titanium is usually liberated from the silicate lattices when reactions (5) and (6) go to the right (see tables II and III). This is well illustrated in the field in West-Greenland; rutile is a very common accessory mineral in the khondalites and kinzigites, the garnet of which formed at the expense of biotite when the rocks were subjected to the high P,T-conditions of granulite facies.

THE STABILITY CONDITIONS OF SPHENE.

In granulite facies sphene has only a very limited chemical stability field. In this facies sphene occurs solely in rocks rich in Ca, its typical mineral association being calcite, diopside, and scapolite (wollastonite). When the content of Mg, Fe, and Al increases in the rocks, so that hornblende, hypersthene, Mg, Fe-garnet, cordierite, etc. are stabilized, sphene disappears either by being completely absorbed in hornblende (and biotite) or by being partly absorbed in titanium-free lime silicates under liberation of TiO_2. Thus sphene will also contribute to the formation of titanic ore under granulite facies conditions.

REMARKS ON THE STABILITY CONDITIONS OF TITANIFEROUS AUGITE.

The liberation of titanium in the hitherto discussed reactions takes place under increasing P,T-conditions. There is also an important regressive mineral reaction which liberates titanium in the same P,T-interval as discussed above. When basic magmatic rock crystallizes, the pyrogenetic pigeonitic augite is able to absorb considerable amounts of TiO_2. Therefore, if basic magmatic rocks of this type are exposed directly to the physical conditions of granulite facies the titaniferous pigeonitic augite splits up into diopsidic augite and rhombic pyroxene with liberation of Ti.

THE GEOCHEMICAL CYCLE OF TITANIUM.

So far, it is evident that the stability conditions of the main calcoferromagnesian minerals are such that titanium and usually iron will be expelled from the silicates in granulite facies. On the other hand, titanic iron ore is connected in space and time with hypersthene-bearing rocks and anorthosites in granulite facies. It is evident that the ilmenite-magnetite grains, being evenly scattered throughout norites, enderbites, charnockites, and some anorthosites, are formed by the metamorphic reactions discussed above. It seems likely, also, that these processes must have some bearing upon the segregation of smaller and larger bodies of valuable titanic iron ore in granulite facies areas.

When hornblende and biotite are altered to rhombic and monoclinic pyroxene in granulite facies, the partial chemical activity of Ti and Fe in the unstable hornblende and biotite lattices will rise because these elements shun the lattices of the newly-formed pyroxenes (32). Consequently, there appear to be chemical forces which tend to make iron and titanium diffuse away from the place of reaction. Although some of the iron and titanium atoms will form ilmenite, magnetite, and now and then rutile, when they are liberated, there will still be a tendency for the elements to migrate along different pathways in

the rocks. Due to structural and compositional heterogeneities in the complexes there are places where these migrating elements again tend to consolidate.

In a previous paper (34) it is shown that the pegmatites in the granulite facies area in West-Greenland are formed by diffusion in the solid rocks and consolidation of the activated atoms, ions and molecules at places where the structure was favorable for the development of pegmatites. Such places are, for example, fissures and other places of low mechanical pressure. Because potassium, sodium, and silicon are the most mobile elements the pegmatites are preferably of quartzo-felspathic composition.[7] The occurrence of biotite, garnet, hypersthene, and ilmenite and/or magnetite in the pegmatites shows that iron, magnesium, titanium, and manganese also are able to diffuse through the solid rocks, although apparently they are less mobile than the alkali elements and silicon.

It is certain that titanic iron ore is a typical minor constituent of the acid hypersthene-bearing rocks in granulite facies. Larger ore bodies, however, seem to be restricted to either deep-seated gabbroic rocks or anorthosites in granulite facies areas (38, 29).

The connection in space of large deposits of ilmenite or titanic iron ore and gabbroic rocks seems natural. There is no reason to doubt that basic magma is the original carrier of titanium. Thus, plateau basalt contains on the average 2.6 percent TiO_2 (14). When this magma intrudes the granitic shell or spreads on the surface of the Earth, the titanium will crystallize in the form of ilmenite or in the high-temperature titaniferous augite.

If these rocks subsequently are affected by regional metamorphism in epidote-amphibolite facies or amphibolite facies (16), the titanium will be absorbed in hornblende, biotite, and sphene. Titanium will be in excess only where there is a great primary concentration of TiO_2 in the rocks so that ilmenite and rutile develop at these low P,T-conditions.

The silicate minerals mentioned above which are able to absorb considerable amounts of TiO_2 are among the most common constituents of rocks in the metamorphic facies in question. They are, therefore, usually found in more or less concentration in any area in which the metamorphosed basic titanium-bearing igneous rocks are situated. Consequently, chemical forces exist which tend to distribute over a large area the titanium originally concentrated in the gabbroic igneous rock. For this reason titaniferous iron ore bodies do not commonly form in epidote-amphibolite facies or amphibolite facies. For the same reason amphibolites, as a rule, have less TiO_2 content than basalts and primary gabbroic rocks.

If the rocks are subsequently recrystallized in granulite facies, however, where they will develop a noritic mineral association, titanium will be liberated from the unstable lattices of hornblende, biotite, or sphene provided the rocks contain sufficient amounts of silicon and sodium, or are subjected to Na- and Si-metasomatism (p. 557 ff.). There will be no tendency to distribute ti-

[7] In opposition to some authors, I think we have good reasons for believing that K, Na, Si commonly are more mobile than are Mg, Fe, Ca, etc. I cannot discuss this in more detail here, but will refer to a manuscript which will be published in the near future.

tanium in small concentration in silicates over a large area, and segregations of titanic iron ore must form at places where the structure and composition in the complex are favorable.

Titaniferous augite and pyrogenetic titaniferous basaltic hornblende are also unstable in granulite facies with excess of silica; thus, a direct metamorphosis in granulite facies of some basalts, as well as Si(Na)-metasomatism, will also liberate Ti and Fe.

I am inclined to believe that the conditions discussed above are the main reasons for the titanic iron ore being connected with gabbroic rocks recrystallized in granulite facies.

The ilmenite-rich dikes and large segregations in anorthosites are not so simple to explain. The origin of this type of ilmenite ore is not explained solely by the liberation of Ti and Fe from silicates in granulite facies, though anorthosites no doubt belong to this facies of rocks. For several reasons which cannot be discussed in this paper, the writer believes that anorthosites [for example the Egersund anorthosite (6) in Norway, and the Adirondack massif in New York (2, 11)] have received their present structure and mineralogical character by regional metamorphic recrystallization in the solid state. The occurrence of titanic ore in anorthosites must be considered in connection with the whole anorthosite problem, or rather the whole granulite facies problem. It is not easy to find the source of titanium in the anorthosite massifs themselves, but I am nevertheless inclined to believe that the ore originated by the breaking up of titaniferous ferromagnesian silicates.

We know that there must have been medium- and large-scale metamorphic migration of elements in combination with the mere recrystallization of rocks in granulite facies. Thus it is evident that H_2O, for example, has been expelled from the hydrous minerals when low-grade rocks were subjected to the physical conditions of granulite facies. The superfluous water, only to a negligible extent, occurs in pores in the rock; most of the water is diffused away from the rocks. Water is no exceptional rock constituent in this respect, though it is indeed likely that water is one of the most mobile substances. There is no reason to believe, however, that the mobility of water molecules along grain boundaries is much greater than the mobility of other atoms, molecules, or ions through rocks (4).

Let us study the geochemical migration of elements through the crust a little further. Unfortunately, there is no means of calculating the velocity of diffusion of the several elements through rocks. We can only state that experiments with solid metals show that the distance over which diffusion can extend through geological time (for example 100,000,000 years) ranges from *a few centimeters* to about *50,000 meters* (Na over WO at 300° C (4)).

For further discussion of the origin of titanic iron ore in anorthosites, the effect of the gravitational field upon diffusion currents is worthy of notice. The writer has discussed the principal rules for the diffusion and chemical stability in the gravitational field (33), and Barth has applied this theory to the distribution of oxygen in the lithosphere (7). It can be shown that elements or molecules with low *fictive density* $= M/V$ (where M = molecular or atomic weight, V = fictive molal volume) tend to be squeezed out of miner-

als or magmas in deeper parts of the crust and diffuse to higher levels where they again consolidate. Elements having strong attraction to minerals or liquids with low density are exposed to the same upward directed chemical forces.

Elements with great fictive density or strong attractions to minerals or magmas with high density tend to move down in the gravitational field, not only because of the gravitational attraction, but also due to chemical bonding forces. The principal elements and molecules thus tending to diffuse up and concentrate above certain levels are H_2O, O, K, Si, Na, (Al), F, Cl, CO_2. The downward migrating elements are principally *iron, titanium, manganese* and most likely *magnesium* due to its tendency to combine into dense ferromagnesian minerals. Calcium seems to occupy an intermediate role and tends to concentrate in the crust between the two groups of elements mentioned above.

The tendency of H_2O and O to be squeezed out of mineral lattices deep in the Earth's crust, and to diffuse upward is clearly indicated by the composition of the upper lithosphere. Thus in granulite facies which comprise rocks formed at great depths, hydrous minerals are scarce, and the degree of oxidation (*e.g.*, the ratio $Fe^{\cdot\cdot\cdot}/Fe^{\cdot\cdot}$) is small. (The norite-enderbite-charnockite series has a lower $Fe^{\cdot\cdot\cdot}/Fe^{\cdot\cdot}$ ratio than the common granodiorite series (23)).

The tendency of Si, K, and Na to diffuse upward through the crust harmonizes very well with the main feature of the deeper parts of the crust. Below the zone of epidote-amphibolite and amphibolite facies which comprise potash-sodium-rich quartzose gneisses, is the zone of granulite facies of rocks. This zone, which only crops out in deeply eroded parts of old folded mountains, comprises a great diversity of rocks. The main gneiss here, however, instead of being the comparatively potash-rich granodioritic gneiss so common in higher zones, is a hypersthene-bearing quartz diorite (24, 20, 34). Furthermore, if large massifs of anorthosite are encountered, they appear to be situated below the quartzose granulite facies gneisses (Egersund, Norway; and Adirondacks). At these low levels the gravitational field tends to squeeze out oxygen, silicon, potassium, and some sodium from the solid rocks and minerals so that here only plagioclase of intermediate composition remains stable, together with pyroxenes, garnet, olivine, and ore minerals. There is also a tendency, however, for the elements of the heavy minerals to migrate down and consolidate at still lower levels where these heavy minerals are stable. This tendency of downward diffusion of ferromagnesian and other heavy elements affects the rocks and minerals at higher levels also. But at the comparatively low temperatures (and pressures) existing in the upper part of the crust the mobility of the elements Fe, Mg, and Ca is so low that large scale stability is by no means developed.

Consequently, there is actually a thermodynamic tendency to separate anorthositic massifs or a more or less continuous anorthositic shell below a certain depth in the crust.

Considering the superfluous Si, Na, and K which are squeezed out of the anorthositic shell, these elements will behave in different ways. Si and Na will tend to consolidate immediately above the anorthositic shell, thus giving rise to Na- and Si-metasomatism. That is, the main composition of the

plagioclase here should be somewhat more acid than in the anorthosites, and, in the P,T-conditions of granulite facies, hornblendes and biotites should split up into rhombic pyroxene and plagioclase, upon liberation of iron and titanium (p. 560 ff.). The required decreasing basicity of the plagioclase when going from basement anorthosites to overlying birkremites, mangerites, enderbites, etc. is actually found in the field (Egersund, Norway; Adirondacks, N. Y.).

It is clear that mechanical movements in the crust will, from time to time, disturb an ideal development of a concentric anorthosite layer so that anorthositic massifs of different size will be intermingled with rocks rich in quartz and potash felspar.

When the upward migrating Na- and Si atoms (ions or molecules) penetrate gabbroic rocks the liberated titanium and iron is usually concentrated enough to develop titanic iron ore "in situ." In the main portion of the rocks which are subjected to the upwardly diffusing sodium and silicon, however, titaniferous silicates such as hornblende and biotite are relatively thinly distributed, and the liberated iron and titanium have no strong tendency to form large bodies of titanic iron ore "in situ." On the contrary, forces exist which tend to make the liberated Ti and Fe migrate downward. The veins and segregations of titanic ore in the basement anorthosites should then be the places where the activated downward diffusing ore elements again tend to consolidate.

With reference to the upward diffusing potassium, this element does not tend to concentrate immediately above the anorthosite massifs. That is so because potassium is strongly attracted to the light potash felspar which is stable at still higher levels. Only part of the potassium will be left in granulite facies, viz. (1) that which was substituted for sodium and calcium in plagioclase, (2) the part which enters the lattice of biotite (it must be remembered that biotite has but a small chemical stability field in granulite facies), (3) due to the great mobility of potassium, potash felspar will be concentrated in secretion pegmatites in granulite facies. Furthermore, sedimentary rocks rich in Al (sillimanite gneisses) should, due to the high chemical activity of Al in these rocks, tend to absorb K in the form of potash felspar (the mass action law).

I would like to repeat that the *directions* of the migrations, and the thermodynamical stability relationships of the several minerals as explained above, are in harmony with the main picture of the position and development of titanic iron ore in the Earth's crust. Whether or not the actual *velocity* of the diffusion processes supports this theory, cannot be decided at present due to the lack of sufficient data.

Let us now briefly follow the titanium which, during weathering and erosion, is brought into sediments. Under medium degrees of regional metamorphism most of the titanium, except when it is concentrated too highly in the sediments, will tend to be dispersed in rather low concentration in biotite, hornblende, and sphene over a smaller or larger area depending on the velocity of migration of Ti.

At low temperature in green-schist facies no biotite or hornblende is formed and Ti can occur only in the different modifications of TiO_2, and in sphene.

In this case, therefore, titanium is leached out from sediments and is often more or less concentrated in Alpine veins (26).

If the sediments are exposed to the physical conditions of granulite facies, however, biotite, hornblende, and sphene become unstable and the liberated titanium (and iron) participates in the geochemical cycle of titanium explained above.

ACKNOWLEDGMENTS.

I would like to express my sincere thanks to Dr. W. H. Newhouse and Dr. A. F. Hagner for critically reading the manuscript and suggesting valuable alterations.

To Dr. B. Bruun my cordial thanks are due for analyzing the minerals.

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May 25, 1948.

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GEOLOGY OF THE CARIBOO GOLD QUARTZ MINE, WELLS, B. C.

A. C. SKERL.

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ABSTRACT.

This account is the result of mapping and studying the geology of the Cariboo Gold Quartz Mine over a period of 20 months with the ultimate object of defining the ore-controls and so indicating the areas to which major development should be directed. It is believed that this objective has been attained to a large degree, although additional geological evidence that may be uncovered during future work might modify some of the present conclusions.

The geological setting of the ore deposits is briefly as follows: The sedimentary country rocks known as the Rainbow Series were severely overturned, intensely drag-folded, and then cleaved. A series of major north-south faults dipping to the east broke the folded rocks into a number of segments, each of which was sliced up by faults parallel to the cleavage. One set of tension fractures developed at right angles to the intense compression during folding and another set perpendicular to the north-south faults were opened up during the later stages of faulting to receive mineralization of pyritic auriferous quartz. The veins so produced are of commercial grade adjacent to the two sets of faults where the fractured ground provided the best channelways for the mineralizing solutions. A third type of vein was formed in strong shear zones developed along or parallel to the axial planes of the major drag-folds.

The high-grade replacement ore that has been the mainstay of the neighboring Island Mountain Mine is very limited in its occurrence in the Cariboo Gold Quartz Mine but it is hoped that appreciable amounts will be found in the unexplored ground on each side of Island Mountain Mine.

The Cariboo district has yielded about 600,000 ounces of lode gold to date and the indications are that ultimately the total lode production from

the known ore-bearing sections and their extensions will equal the placer production of over 2,000,000 ounces of which the Cariboo Gold Quartz Mine should produce three-quarters.

INTRODUCTION.

NUMEROUS reports have been published on the geology of the Cariboo District, beginning with those of Dr. G. M. Dawson in 1876–77 (1).[1] The oustanding account of the area was given by Amos Bowman in 1888 (4), as a result of field work in 1885–6, although his untimely death in 1894 prevented the writing up of the details of the individual placer creeks. His field sheets (5) have proved invaluable to miners in the district ever since. He laid the groundwork for all subsequent geological surveys in the area; thus his mapping of a large scale anticlinorium has not been challenged. The overfolding of the Cariboo schists, depicted in his main cross-section, was ignored in subsequent publications until 1945 when Benedict (13) described the overfold in the Island Mountain Mine. Bowman accurately described with assay values the veins on which the present producing mines were started over forty years later. He also pointed out that the auriferous veins were confined to the "Cariboo Series."

In 1926 the Geological Survey of Canada published a Memoir by Johnston and Uglow (6), in which the authors described numerous auriferous vein outcrops and placer workings in the Cariboo district. In 1935 Hanson (9) gave a detailed account of the Geology of the Barkerville Gold Belt. He made a study of the newly opened Cariboo Gold Quartz and Island Mountain Mines and produced a map of the surface geology. This work was extended by Davis in 1937 (10) in the Island Mountain section and by Lang in 1938 (11) in the Keithley Area.

In 1945 and 1946 Gordon Brown made a detailed study of the gold belt with a view to locating favorable auriferous areas for the Barkerville Mining Company in their extensive holdings.

However, the first paper to elucidate the structural control of the ore-bodies was that of P. C. Benedict in his excellent account "Structure at Island Mountain Mine, Wells, B. C." (13). He described the control exercised by the Aurum fault on the vein deposits and by the overfolded sediments on the replacement deposits.

In June 1946 the complete geological mapping of the existing underground openings at the Cariboo Gold Quartz Mine was started as a basis for a subsequent study of the various ore bodies. To date 16 of the 18 miles of drifts and cross-cuts have been washed down and mapped in detail. In addition the exposures in Lowhee Gulch have been mapped.

This work has been done by Messrs. W. Cameron (resident geologist and now also chief engineer), M. Guiget (assistant geologist), C. McFeeley (student assistant) and the writer. During the later half of the period several thousand feet of diamond drilling was directed and logged by the same group. The geological setting of most of the ore-bodies has now been studied and the ore reserves entirely recalculated.

[1] Numbers in parentheses refer to Bibliography at end of paper.

A report on the property of Williams Creek Gold Quartz Mining Company by the present writer appeared in 1948 (14). It contained a preliminary account of the geology of the Cariboo Gold Quartz Mine but was not illustrated.

TOPOGRAPHY AND LOCATION.

The mining claims embrace an area of 2,868 acres within a block of ground 4 miles long by 2 miles wide, situated around the north end of the Jack of Clubs Lake (elevation 3,900 ft). They extend for 2½ miles to the east up the Lowhee Gulch to its head and for 1½ miles to the west around the Island Mountain Mine to Red Gulch. Part of the north boundary reaches to Williams Creek. The township of Wells is within the claims at the head of the lake which is 55 miles from Quesnel, the present terminus of the Pacific Great Eastern Railway .

In three areas the property attains an elevation of over 5,000 ft, namely to the north-east on Barkerville Mountain, to the south on Cow Mountain overlooking the lake and to the west at the head of Mosquito Creek.

The topography is moderately steep, glacial action having smoothed off an originally rugged surface and filled in the valleys.

The pre-glacial drainage of the area has been considerably altered and reversed in some places so that the tracing of old channels is a major problem for the placer miners in the district.

BRIEF HISTORY OF THE MINE.

Numerous but unsuccessful attempts were made to mine the auriferous veins of the Barkerville Gold Belt from the 1860's onward but it remained for the enthusiasm and persistant endeavor of Mr. Fred M. Wells to make hard-rock mining profitable in the area. After several years of careful prospecting he formed the Cariboo Gold Quartz Mining Company Ltd. in 1927 with Dr. W. B. Burnett (President) and Mr. O. H. Solibakke as fellow directors.

The setbacks, disappointments and financial difficulties of a small independent gold mining company were overcome so that a dividend was declared for the first time in 1935.

To January 1948 the following was achieved: Ore milled, 1,004,942 tons; bullion produced, $14,083,056; dividends paid, $1,679,968; ore reserve, $2,660,000.

Peak production was reached in 1941 ($1,900,009) but since then the adverse factors of increasing cost of supplies and labor have led to a loss being incurred each year since 1944 and the small amount of development work since 1942 has placed the company in the position of having insufficient better-grade ore accessible to mining that could off-set the greatly increased costs of production.

REGIONAL GEOLOGY.

(Modified after Hanson.)

The oldest rocks of the district are known as the Cariboo Series. They are not fossiliferous, but from their structural position, degree of metamorphism

and similarity to assumed Precambrian rocks farther south, they are believed by Hanson to be of Precambrian age. They may, however, as thought by Bowman, represent highly metamorphosed early Paleozoic sediments in which all fossil evidence has been destroyed. They consist of quartzites, argillites and limestones folded into an anticlinorium trending northwesterly for over fifty miles and exposed over a width of fifteen miles.

In some areas the Cariboo Series is intruded by a few sills and dikes of quartz porphyry known as the Proserpine intrusives. Overlying the northeastern limb of the anticlinorium in mild unconformity is the Slide Mountain Series of Upper Paleozoic age, consisting from bottom to top of conglomerate, crinoidal limestone, banded chert, argillite, and basaltic lavas. The southwestern limb of the anticlinorium is overlain unconformably by Jurassic argillites and basalts called the Quesnel River Group.

Cariboo Series.—In the Barkersville area Johnston and Uglow divided the Cariboo series into three formations: Pleasant Valley, Barkerville, Richfield. Of these the Richfield, which contains all the known lode gold deposits of the district, was considered the lowest and has been further subdivided by Hanson into five members, namely: Baker, Rainbow, B. C., Lowhee, Basal.

A suspicion that Hanson entertained in his discussion and then dismissed appears to be true, namely that the Rainbow and Lowhee members are one and the same and similarly the B. C. and Basal, on opposite sides of intense folds, although all four were mapped as different horizons. This simplified interpretation is shown in the accompanying plan (Fig. 1) in which the geology is projected to one horizon. The present writer has still to finish mapping the surface exposures to check this interpretation of the work of previous geologists. Benedict has demonstrated that the rocks in the Island Mountain Mine are all on the lower limb of an overturned anticline, thus inverting the succession set up by Hanson. The drag-folding observed in the Cariboo Gold Quartz Mine leads to a similar conclusion.

This inversion of the succession may affect the accepted order of all the strata of the Cariboo Series.

Rock Types in the Mine.—The rocks encountered in the mine consist of a well-cleaved series of metamorphosed sediments varying in composition according to the percentage present of the following main ingredients: quartzite, argillite, dolomite, limestone, talc, tuff, porphyroblastic ankerite and dolomite.

Minor amounts of graphite, pyrite, magnetite, mariposite (?) and secondary quartz may be present. The dominant types are: dark grey quartzites, black argillaceous quartzite, interbedded argillite and quartzite or dolomite, black argillite, black and white limestone, dolomite, dolomitic argillaceous quartzite, porphyroblastic talcose quartzite, dolomitic quartzite, tuff.

Hanson divided the Rainbow member in the Caribbo Gold Quartz Mine into four:

No. 1 Band—fissile argillite and quartzite
No. 2 Band—fissile quartzite
No. 3 Band—fissile argillite and quartzite
No. 4 Band—fissile quartzite

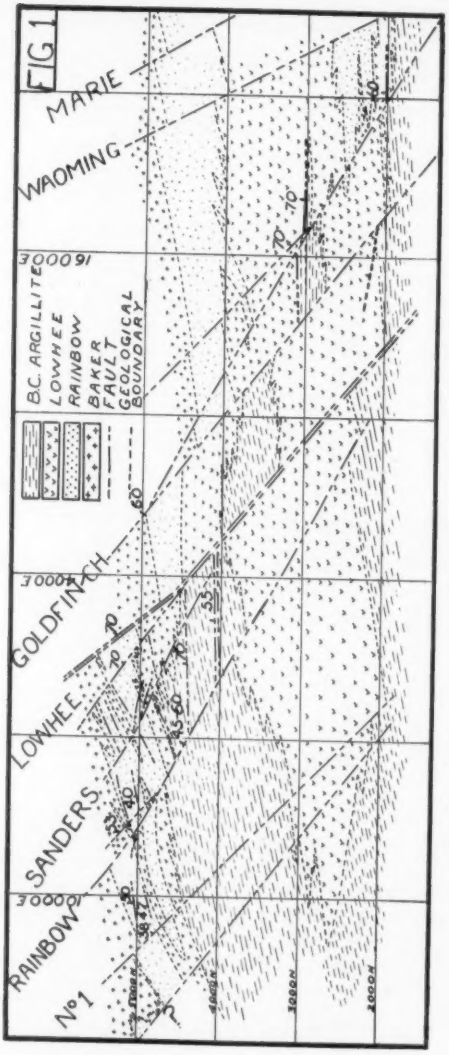

FIG. 1. Geology (known and inferred) projected to 4,000 ft elevation.

No. 2 band is largely light colored porphyroblastic talcose quartzite and in the past has been mapped as a unit throughout the main workings as a uniformly dipping bed. Nos. 1 and 3 bands are alike and were only distinguished by their position relative to No. 2, and No. 4 band is dolomitic and commonly resembles No. 2.

The following succession has now been adopted for the metamorphosed sediments in the mine with the youngest at the top:

B. C. Argillite—Black argillite with quartzitic bands.
Lowhee —Light colored dolomitic argillites with quartzite and dolomite bands.
Rainbow —Dark quartzites with interbedded quartzites and argillites sometimes dolomitic.
Baker —Calcareous and dolomitic argillites, limestone and tuff.

The recent detailed mapping has brought out the fact that the various rock types have a very lenticular habit and that individual contacts cross the cleavage at all angles. Dragfolding is often observed and it is suspected that the

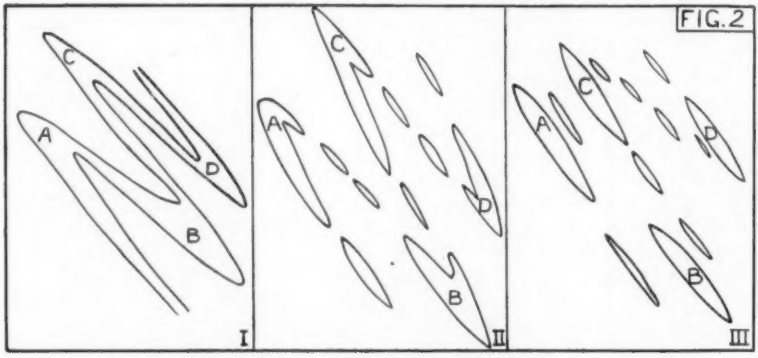

FIG. 2. Diagram to illustrate formation of lenticular structure.

lenticular nature of the rocks is due to the attenuation and slicing off of dragfolds owing to the intense pressure that produced the cleavage (Fig. 2). Hanson noted the variation of the rock types along the "bedding" (actually cleavage) and attributed it to original sedimentation.

Dynamic metamorphism of the rocks along certain dolomitic horizons, which may be limbs of folds, has produced the light colored porphyroblastic talcose quartzites. Thus, the so-called No. 2 band appears to be in part a large elongated infold of the Baker horizon in No. 3 Zone and in part a similar fold of the Lowhee horizon in Nos. 1 and 2 Zones (Fig. 3).

The occurrence of light colored highly siliceous rocks with these talcose horizons suggests that bleaching has taken place by oxidation of the graphitic material in an original dark quartzite. A source of such oxygen might have been the conversion of ferric iron to the ferrous state as in ankerite.

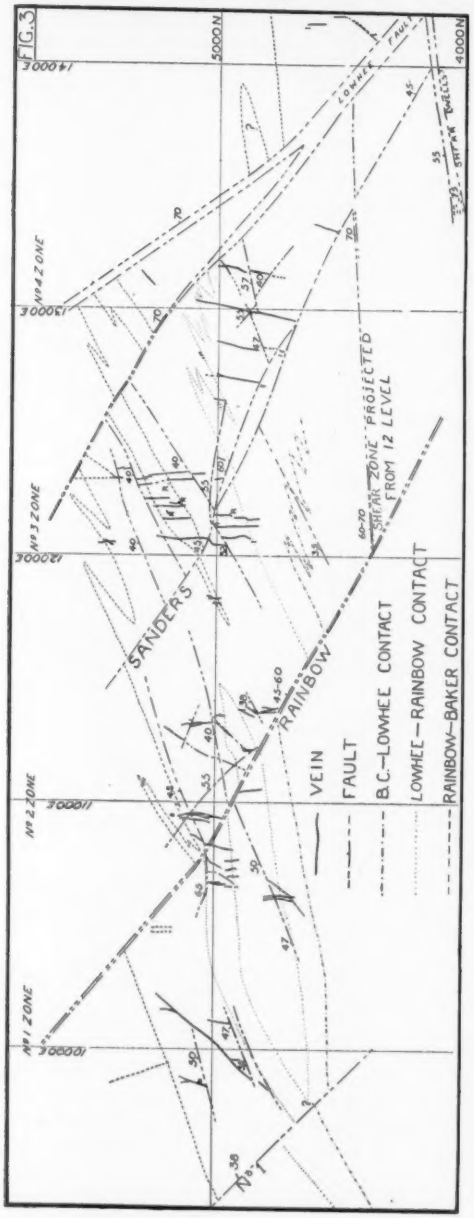

FIG. 3. Main contacts and veins at 4,000 ft elevation.

A rock that is regarded as volcanic tuff, although it is commonly contaminated with normal sedimentary material, has been mapped near the Baker contact and occasionally elsewhere in the series. At Island Mountain it is called "altered diorite" although with considerable doubt.

An interesting feature is the absence of any intrusive rocks in the present mine workings and in the surface exposures, mapped to date. The nearest authentic igneous rocks appear to be the Mount Murray Sills mapped by Uglow in 1922 on Slide Mountain about 5 miles to the Northeast. The so-called quartz-porphyry mapped by Hanson near Barkerville seems to be a metamorphosed grit.

FOLD STRUCTURES.

The structural history of these rocks is difficult to reconstruct especially as they can only be correlated by their lithology. It is usually necessary for the sediments to be fossiliferous or good marker horizons to be present before intricate folding can be unravelled. In the present case there are no fossils and the old marker No. 2 band is suspected to be a zone of metamorphosed dolomitic rocks of more than one horizon. The new mapping has recognized a volcanic tuff, although it is in many places impure from admixed normal sedimentary material; so much so that metamorphism has made it hard to distinguish from argillaceous quartzite. The normal position of this rock is immediately north of the limestone horizon at the so-called Baker contact. The combination of the two rocks provides a fair marker for disentangling the folding and for directing the search for the closely associated rich replacement ore.

The following sequence of events appears to account for the arrangement of the rocks immediately preceding the faulting described in the subsequent section.

1. Formation of a normal sedimentary series with calcareous and dolomitic rocks associated with volcanic tuffs at the bottom and passing up through dolomitic and muddy sandstones to sandstones and dolomites with muds predominating at the top.
2. Uplift producing a large elongated dome.
3. Compression from the northeast and southwest throwing the simple dome into an anticlinorium.
4. Increased compression producing overfolds.
5. Continued pressure forming cleavage which in the mine area dips 45° NE.
6. Consequent heat metamorphosing the rocks to quartzites, slates, etc., with porphyroblastic dolomite and ankerite in the horizons containing the necessary ingredients.
7. Folds become greatly attenuated and the drag-folds sliced off.
8. Increasing metamorphism along certain dolomitic horizons produced highly talcose zones.

In the Island Mountain Mine the drag-folds have a regular pitch of 22° NW towards the nose of the anticlinorium. The available evidence to date in the Cariboo Gold Quartz Mine is a similar pitch of 20° NW.

Owing to the discontinuous nature of most of the exposures underground much of the details of the minor folding has to be inferred. Drag-folding can

be observed on all scales as illustrated. Thus Figure 4 shows the attenuated folding in a piece of drill core. Figure 5 is a sketch of similar folding in the wall of the 15 main cross-cut. Figure 6 is the cross-section along coordinate 12,060 E with the same type of folding. Figure 7 is a generalized section along 12,600 E that spans the company's claims.

In many of the exposures underground, especially of the interbedded quartzites and argillites, numerous lenses of the harder rock are seen aligned in the cleavage of the softer rock. It is believed that these lenses, which range in size from a fraction of an inch to several feet and possibly tens of feet across, are not due to original sedimentation but have been produced from the

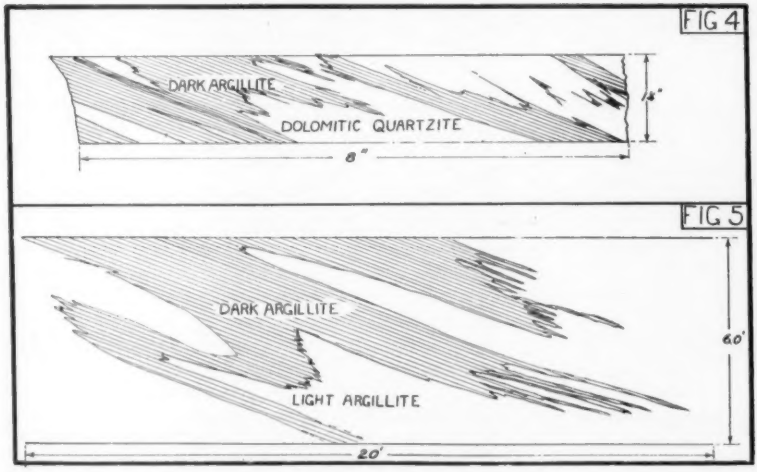

FIG. 4. Drag-folding in diamond drill core.

FIG. 5. Drag-folding in wall of 15 main cross cut.

attenuation and slicing off of drag-folds as indicated in the diagrams of Figure 2.

The so-called No. 2 band was found to have a discontinuity along its strike pitching about 24° to the northwest in the No. 3 Zone. This gap may be a large scale example of the slicing off of a drag-fold but the more likely explanation is that the eastern section is a major drag-fold of the Baker horizon with Rainbow rocks on each side, while the western section is an infold of the Lowhee dolomitic rocks (Fig. 6).

Intense metamorphism has produced a light greenish colored talcose dolomitic quartzite as the dominant rock type in this so-called No. 2 band, but there is a significant amount of calcareous carbonate corresponding to the Baker rocks in the eastern section and much greenish argillite in the western suggesting the Lowhee rocks (Fig. 3).

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In 1945 Benedict postulated that there should be a large syncline south of the Island Mountain Mine. In Figure 1 a map has been prepared projecting all the known and inferred geology to the 4,000 ft. elevation. Here the B. C. Argillite of Hanson is shown as occupying a large syncline in the position expected by Benedict, with a further anticline of the Lowhee formation beyond. To the east the plunge of this anticline brings the Rainbow rocks to surface at the Cariboo Canusa shaft and farther east these Rainbow rocks unite with the main strike around the end of the syncline in Williams Creek ground. Figure 7 illustrates this folding in cross section.

FAULT STRUCTURES.

Wherever there are sufficient exposures, such as in the mine workings, it is found that a series of northerly striking and easterly dipping faults have

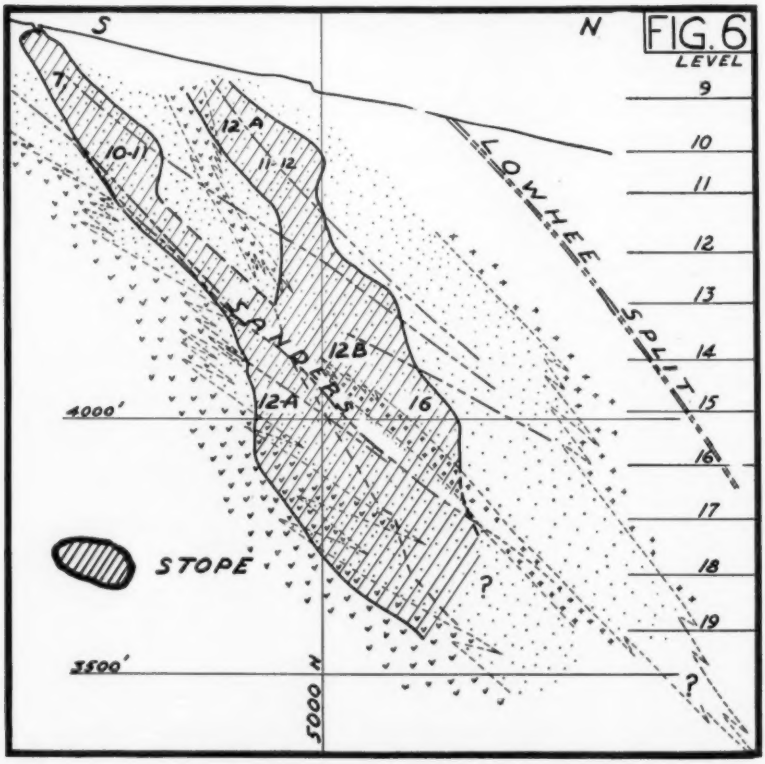


FIG. 6. Longitudinal vertical projection along 12,060 E.

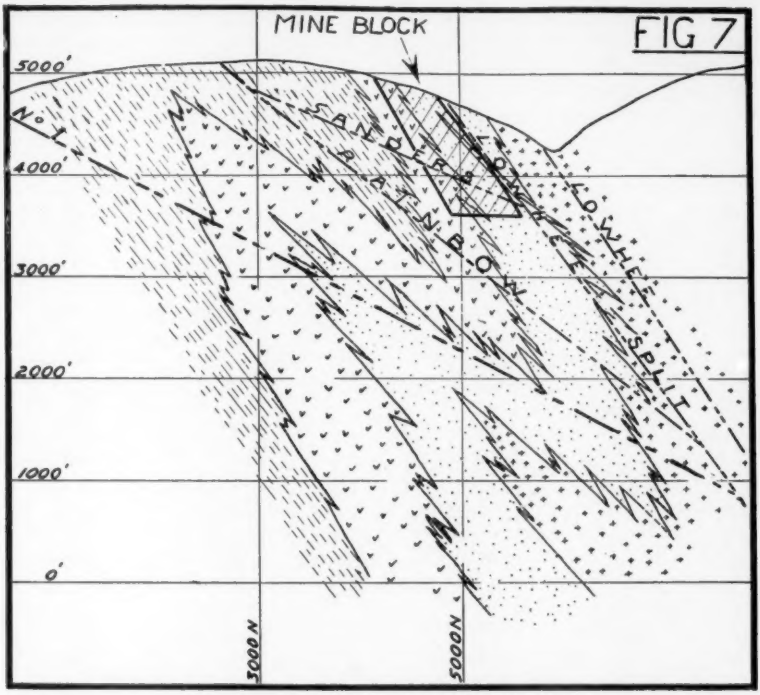


FIG. 7. Generalized section along 12,600 E.

cut the sediments into numerous segments. The easterly block in all cases has moved south and the apparent displacement varies from a few feet to a thousand feet and more. These faults are spaced 500 to 1,000 feet apart and the dip in general increases from about 40° in Island Mountain for the Aurum fault to nearly vertical for the Sirius fault 3 miles to the east (Figs. 1, 3).

The apparent horizontal throws and average dips on these faults are as follows:

No. 1	100′	36°E
Rainbow	300′	52°E
Sanders	20′	47°E
Lowhee	1400′	70°E

Assuming that the faults maintain these average dips No. 1 and Sanders will coalesce with the Rainbow at 2,000 feet and the Lowhee at 500 feet respectively below the present bottom level (20). If the Rainbow maintains its present attitude then it will join the Lowhee 3,000 feet below the bottom level and the Aurum fault from Island Mountain will come to the same position.

In any vertical section of the mine, however, other faults that outcrop farther west will come in at depth (Fig. 8).

Another important set of faults parallels the cleavage; some of them have had considerable movement if the amount of gouge can be taken as an indication. The larger of these so-called "bedded" faults are spaced about 100 feet apart horizontally and dip 45° NE (Fig. 3). Numerous minor faults lie between them and are difficult to trace because they merge into the cleavage. It is believed that the two main sets of faults described above are complimentary and are the result of the continued pressure from the northeast. The rocks were compressed beyond their limit and fractured. The cleavage planes were the weakest direction and the north-south faults form an equal angle with them and the direction of compression.

Thus the unit blocks of ground that moved relative to each other were a series of slabs inclined at 45° to the northeast and each bounded on the northwest and southeast by easterly dipping faults. The overall movement was such that an easterly block always moved farther than the next one to the west.

The movement on the bedded faults according to the above analysis should be to the left which is the actual case when the evidence can be interpreted.

A third direction of faulting which is believed to have antidated the other two is shown by large shear zones up to 15 feet wide that appear to occupy or to parallel the axial planes of the major drag-folds. The B. C. vein occupies such a shear parallel to the axial plane of the major syncline of B. C. argillites.

Other examples of these shears are discussed later under the heading of "Vein Deposits."

There are numerous minor faults with a variety of strikes and dips. The north-south and the "bedding" faults have many branches and sub-parallel fractures so that the fault zone may be as much as one hundred feet wide.

VEIN DEPOSITS.

As a result of the severe compression from the northeast described above a series of vertical tension fractures were formed at right angles to the direction of pitch of the folds.

During their movement the north-south faults produced another set of tension fractures at right angles to their strike and dipping steeply north (Fig. 3).

Continued movement opened up both groups of these fractures enabling mineral solutions to invade the broken zones near both the north-south and the "bedded" faults and produce auriferous quartz-pyrite veins. Some mineralization took place in the faults themselves.

Further movement along the faults dislocated some of the veins for a few feet and crushed the quartz in the faults producing drag ore. The veins perpendicular to the pitch are known as transverse veins since they cut the strike of the formation nearly at right angles. Those in the fractures at right angles to the north-south faults are diagonal veins since they cut the strike of the formations obliquely.

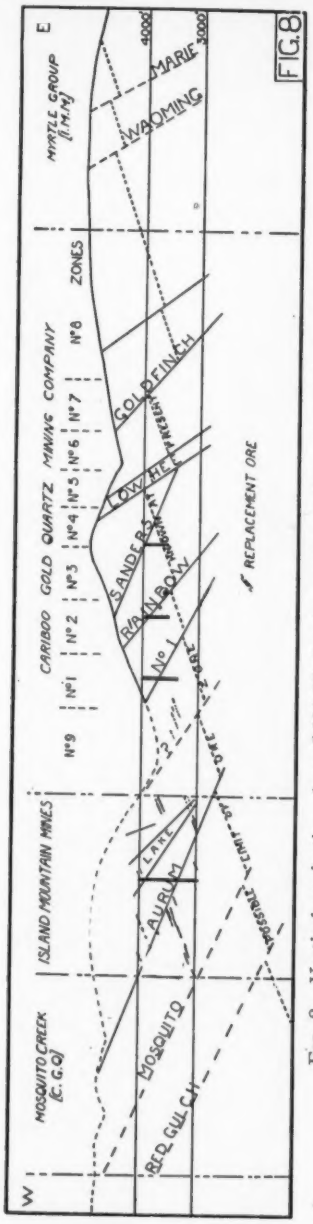


FIG. 8. Vertical projection along 5,000 N showing major faults and possible trend of ore zones.

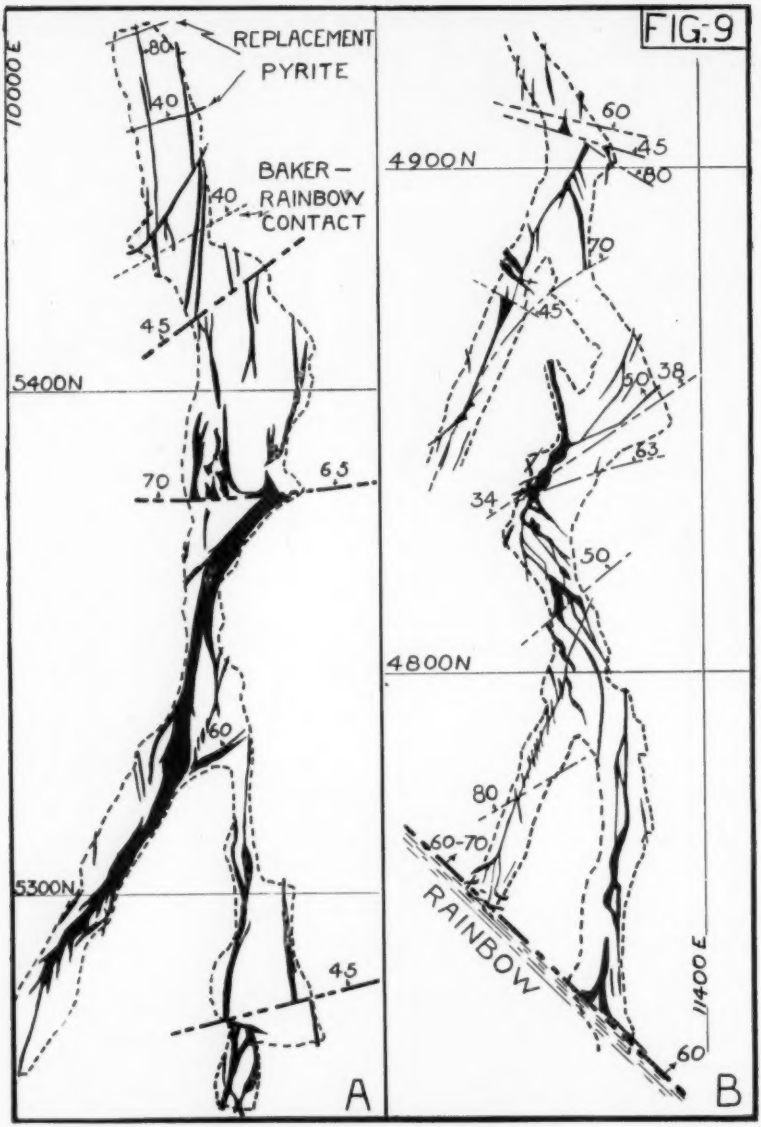


FIG. 9. A. Plan of 19–2 stope vein system. B. Plan of 15–15 B stope vein system.

These two sets of fractures commonly join giving veins of a complex pattern although one direction generally dominates in a given vein (Fig. 9).

Benedict states that only diagonal veins are large enough to mine at Island Mountain and that they have a steep dip to the south whereas the transverse veins are too small and dip 50° SE, a direction of low dip not seen in the Cariboo Gold Quartz Mine.

Bedded faults are almost invariably associated with the ore-bodies, as can be seen in both the plans and sections of the various veins. Moreover, the veins are mostly wider and of higher grade directly against these faults as well as the north-south faults. This is strong evidence for assuming that the fractured rock immediately adjacent to the faults was the channelway for the ore-bearing solutions.

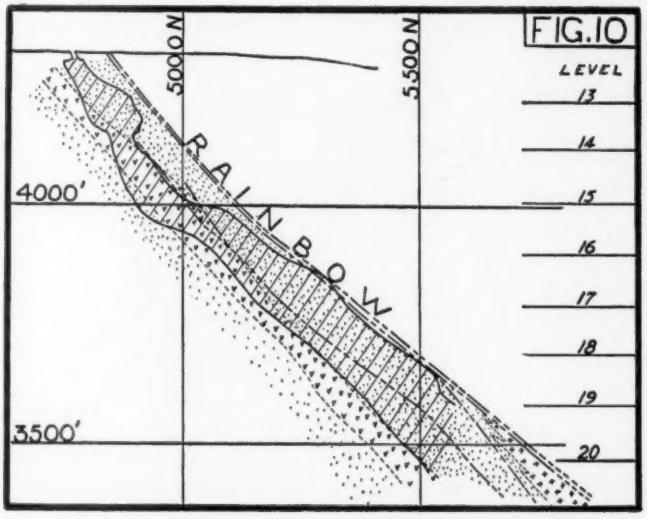


FIG. 10. Longitudinal vertical projection along 10,660 E.

The transverse veins normally persist for about 100 feet and the diagonal for 200 feet from the north-south faults, but the sections that can be stoped are often much shorter. Generally they do not pass into the Baker limestone horizon or far into the so-called No. 4 dolomitic horizon. Commonly they do not cross the No. 2 band but a separate set of veins occupy it.

Owing to the general dip of the country rock the veins have much greater persistence in depth than in strike but eventually they are cut off by a north-south fault unless it so happens that the apparent dip of the north-south fault in the plane of the vein coincides with that of the cleavage in that plane as in the case of the transverse veins associated with the Rainbow and Sanders faults

(Figs. 6, 10). Folding of the coutry rock may increase or decrease the length of a vein at various levels (Fig. 11).

As is usually the case with veins formed in tension fractures, they are not continuous exactly in the same plane but offsets and gaps of a few feet occur in the vein filling. However, an essential continuity of mineralization can frequently be traced from level to level through the old stopes to a degree not appreciated in the past. This fact is of great importance in the planning of

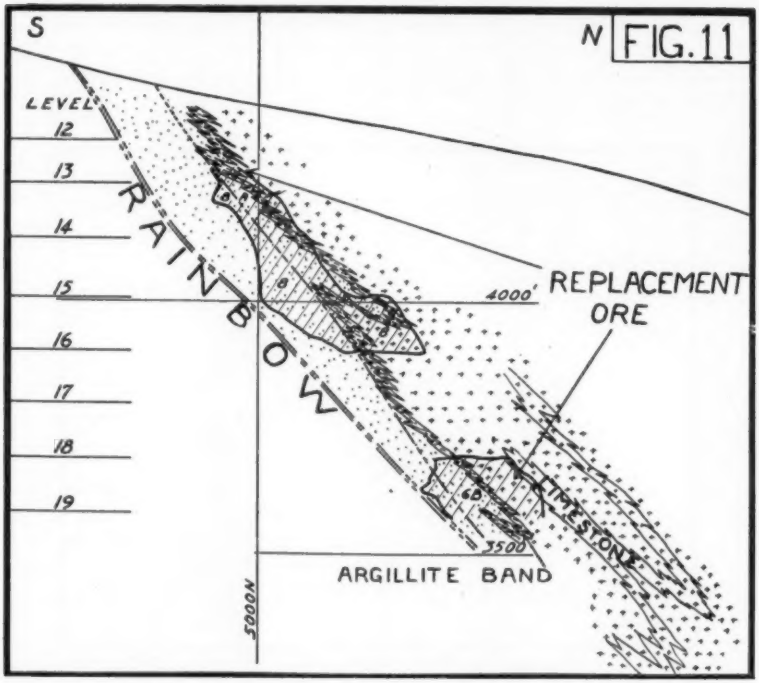


FIG. 11. Longitudinal vertical projection along 10,950 E.

development work. The use of this knowledge has recently led to the discovery of extensions to ore-bodies previously considered of limited extent. An unusual feature of the veins is the absence of wall rock alteration apart from the pyritic dissemination.

The "bedding" faults are often closely associated with the transverse veins.

Diagonal veins on the hanging wall side of the north-south faults are cut off at depth with their enclosing country rock against the faults but upwards they extend farther away from the influence of the faults and give out.

The diagonal veins are more numerous against the large north-south faults, such as the Rainbow and Lowhee, and uncommon against the weak faults, such as the Sanders (Fig. 12).

Since the fractures were opened up and then mineralized towards the end of the movement along the north-south faults, no offset section of a diagonal vein that abuts one of these faults can be sought for on the other side. Another set of veins will be found, however, in the corresponding country rock.

In the case of transverse fractures, since they are considered to have developed before faulting, it is possible that corresponding segments on each side of a fault opened up equally during movement to receive the subsequent mineralization. The actual solid vein material, however, never was continuous so

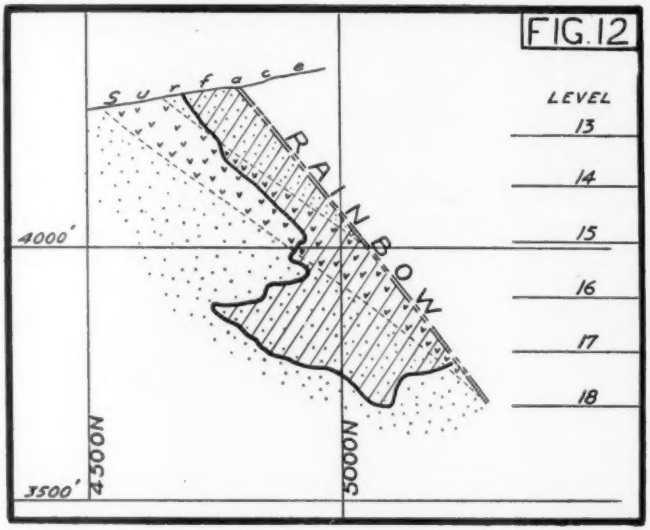


FIG. 12. Longitudinal vertical projection of No. 7 vein.

that although correspondence can often be seen on each side of a fault, especially the Sanders, the tenor of the ore may be very different. In some instances there has been movement along the transverse fractures, making them "tear" faults.

In the Cariboo Gold Quartz Mine there are five major north-south faults that have produced fracture zones that became mineralized with auriferous quartz veins; from northwest to southeast in order they are known respectively as No. 1, Rainbow, Sanders, Lowhee and Goldfinch. Of these only the zones around the first four have been explored in any detail so far. To the northwest there is room for one more fault in Cariboo Gold Quartz ground if the customary spacing persists. Nearly all the ore found in the mine

to date has been within 250 feet horizontally of one of these north-south faults and probably 75 percent has been within 100 feet. Since the faults are never more than 700 feet apart, only a few small sections have been entirely unproductive.

A third type of vein that has recently become important is the so-called A-vein type for which the strike conforms to that of the cleavage but the dip is steeper as defined by Uglow. The best example is the B. C. vein at the east end of the company's property. At the surface it has a known length of 2,400 feet and an average width of 20 feet, proved by stripping. It strikes nearly east-west and the dip averages 70° north to the 15 level at 850 feet below the surface. The cleavage makes a small angle to it both in strike and dip. The vein appears to parallel the axial planes of the major drag-folds and possibly occupies such a plane localized by a major syncline of B. C. argillite.

At least one and in places both walls are defined by a strong fault gouge but the evidence available is insufficient to suggest the amount of movement involved in the plane of the vein.

At about 1,000 feet horizontally into the footwall of the B. C. vein the Cariboo Canusa workings have encountered a parallel vein averaging 12 feet wide. No ore has been found on it to date but the 5 percent of pyrite carries gold values.

It may be of significance to note that in the main mine on the 12 level of No. 2 Zone a strong 10-foot wide shear zone mineralized with 25 percent quartz and some pyrite was found in a long cross-cut in a similar geological position to that of the B. C. vein and with the same attitude. The same shear was cut on the 15 level in No. 4 Zone. A 50-foot extension of the main south cross-cut on 15 level in No. 3 Zone should find this shear in the favorable situation of being immediately against the hanging wall of the Rainbow fault (Fig. 3).

At another 400 feet into the footwall country another strong shear was encountered in No. 4 Zone that corresponds to the so-called Wells Shear on the surface where there is a large and apparently irregular mass of poorly exposed quartz lying against the Sanders fault and which in places carries good gold values.

REPLACEMENT DEPOSITS.

An analysis of the production figures for the Island Mountain Mine from 1934 to 1944 shows that the total of one million dollar dividends was derived from the 100,000 tons of sulphide replacement ore averaging 0.83 oz gold per ton although 300,000 tons of 0.34 oz ore were milled as well.

It is, therefore, surprising that a more vigorous search was not made in the past for this rich type of ore at the Cariboo Gold Quartz Mine.

In 1944 a body of replacement ore was encountered by accident when stoping a transverse vein in the Rainbow zone but until recently no attempt was made to follow up the discovery with systematic exploration elsewhere.

Benedict describes the replacement deposits at Island Mountain as pipes of massive pyrite with a remarkable persistance along the 22° plunge of the drag-folds. With a cross-sectional area of only 100 square feet some extend

for a distance of 1,000 feet. Others are so short, however, that they are better described as lenses, although they may be repeated along the plunge.

These deposits have presumably been formed by the replacement of limestone with a favorable structural situation and composition. Detailed exploration and mapping show that the limestone is not continuous, probably due to original gaps in sedimentation and to squeezing out on drag-folds.

The favorable limestone appears to be the first one encountered in the Baker Horizon above the Rainbow quartzites and argillites. In places the transverse veins penetrate to this horizon but stop there, presumably because of the incompetent nature of the limestone. In some such cases the replacement ore is found at these junctions, so that it is possible that the mineralizing solutions spread from the fractures in the quartzites into the limestone horizon where conditions were favorable. Such an association is evident in the case of short lenses of replacement ore in the Cariboo Gold Quartz Mine arranged like wings on each side of veins where they cut lime horizons not only at the Baker contact but also in the "No. 2" and "4" bands.

Until April 1948, no important replacement body had been found at the Cariboo Gold Quartz Mine that was comparable with the greatly elongated deposits at the Island Mountain Mine. However at that time stoping operations on a small vein (8A) at the Baker contact on the 13 level of the No. 2 Zone disclosed a body of high grade replacement pyrite apparently occupying the trough of a synclinal drag-fold. The width is 12 feet and so far a horizontal length of 20 feet has been opened up. This deposit appears to be identical with the more persistent replacement ore-bodies at Island Mountain and so exploration is being directed towards its projected position on other levels.

Until this new discovery the main replacement ore that had been mined consisted of a series of overlapping lenses in the footwall of a black limestone mass, forming a tabular deposit extending 100 feet along the strike and possibly 100 feet on the dip. Owing to the interleaved country rock the average grade of the stope was no higher than mine average.

The individual lenses appear to have the customary westerly pitch and the higher lenses overlap the lower ones, suggesting overturned drag-folds. The pyritic material as a whole occupies an area in the replacement horizon that lies along the underside of a large lenticular mass of black limestone within 200 feet of the Rainbow fault. Diamond drilling and drifting show that the replacement ore does not go farther than the upper edge of the limestone lens, which here reaches a little above the 18 level. On the 19 level this replacement ore is mostly very thin and has a bed of tuff in the hanging wall.

On the footwall side of the Rainbow fault on the 18 level some narrow replacement ore has been followed for 140 feet, half of which makes fair ore when mined with the associated transverse veins in 19–5C stope. It is in three closely spaced layers up to 0.5 feet thick but thinning out gradually away from the Rainbow fault and giving place to sporadic coarse scheelite, galena, and sphalerite. The layer farthest into the Baker rocks overlaps the others towards the west which, combined with the normal pitch, suggests attenuated drag-folds. Much of the country rock is highly silicified near this replacement pyrite but a bed of altered tuff is recognizable in the footwall.

Recently a pipe of replacement sulphide in No. 2 band of No. 1 Zone was proved for 50 feet before it pinched out. Its lenticular cross-sectional dimension was 5 feet by 1 foot maximum width. The more severe folding and the slicing of drag-folds are probably the explanation for the limited size of these deposits at the Cariboo Gold Quartz but more favorable conditions may be found in the area now being explored between these present workings and Island Mountain. Two small replacement bodies have already been found on each side of the old main cross-cut on the 2,000 level.

As at Island Mountain Mine, the margins of these replacement deposits are characterized by coarse-grained pyrite of low gold content, granular gray mottled mixed carbonates, silicification of the limestone, and pinching out of the limestone.

MINERALIZATION.

The angular outlines of the veins, their branching nature, and the unaltered wall rock suggest that they were emplaced by dilatory pressure, rather than by replacement of the country rock.

About 1 percent by volume of the veins consists of vugs containing well terminated quartz crystals.

The veins mined are characterized by pyrite that may occur in a variety of ways:

(a) masses up to 1 foot across and occasionally larger; (b) scattered cubes and rare pyritohedrons of pyrite throughout the vein; (c) streaks of pyrite along the walls and down the centre of the vein.

The veins of economic grade have at least 5 percent pyrite by weight and generally 15 percent. However, some veins have sections with 60 percent pyrite that are still too low grade to mine.

Most of the gold is in small fractures in the pyrite but coarse "free" gold is frequently seen in the quartz and is then often associated with hair-like crystals of the lead and bismuth sulphide cosalite ($2PbS, Bi_2S_3$). The more massive galeno-bismutite (PbS, Bi_2S_3) may also be present.

Both of these bismuth minerals commonly contain fine particles of gold and it is suspected that the high tailing loss incurred when ore is milled containing much of these sulphides is because they do not react with cyanide and so form a protective coating on the gold. In the early days of the mine the cosalite was mistakenly known as gold telluride. So far as is known neither free gold nor the lead and bismuth minerals have been recognized in the replacement type of ore. The cosalite is sometimes found without any associated gold but normally it is a good indicator of high-grade ore.

The needle-like mineral rutile has been found occasionally but so far in veins that are barren of gold. Bunches of argentiferous galena and more rarely sphalerite and pyrrhotite occur at random in the veins. Coarse scheelite is frequently observed.

Old reports mention the presence of arsenopyrite but this appears to be a case of mistaken identity for a dense finely crystallized "steely" pyrite which incidentally appears to be a good indicator of gold values. The wall-rock

around the veins is commonly impregnated with numerous pyrite cubes up to a foot away and sometimes more. Usually this mineralized wall-rock is very low grade but sometimes it is as good as the vein being mined.

The replacement ore consists of massive crystalline pyrite and usually the finer the grain the better the grade, *e.g.* up to 5 oz per ton. The very coarse grained (above ¼ in.) is usually very low grade, *e.g.* 0.10 oz per ton. Normally there is little or no quartz in this type of ore. Near its edges where it is partly country rock and also thinning out, the minerals galena, sphalerite and scheelite are found as well. A gangue of coarse-grained gray and white carbonates is often found around the limits of this ore.

The paragenesis (order of mineralization) appears normal and E. W. Johnson (8) gives the following succession: carbonate, quartz, pyrite, sphalerite, chalcopyrite, galena, argentite, cosalite, galeno-bismutite, gold, quartz.

The carbonate is mostly ankerite and it is fairly common, especially where the country rock contains carbonate. Sericite is often present in small amounts and so is graphite derived from the wall-rock.

In a report by the American Cyanamid Company (12), the following analysis is given for ore from the Cariboo Gold Quartz Mine:

Gold	0.707 (oz)	Carbon	0.15
Silver	0.07 (oz)	Zinc	0.08
Insoluble	75.26	Arsenic	0.068
Iron	10.27	Bismuth	0.025
Sulphur	10.36	Copper	Tr.
Lead—less than	0.02		

In width the veins vary from a fraction of an inch up to zones 30 feet wide consisting of quartz veins and veinlets with country rock between (Fig. 9).

Usually stopes are three to six feet wide, with branches in either wall. On the average, only 40 percent of the rock broken is actual vein material, so that the coarse pieces of barren country rock are used for fill. In many cases in the past, enough fill for a stope has been provided by the hand-picked waste. With the introduction of scrapers an outside source of fill became imperative.

Most stopes are less than 100 feet long but they may reach a width of nearly 50 feet because of the closely spaced parallel veins and stringers occupying a particular country rock and adjacent perhaps to a fault originally responsible for the formation of the fractures that they occupy. The largest example of such a stope is the area known as 12–4 and 13–4 where a number of short veins both transverse and diagonal occupy the immediate footwall and hanging wall of the Rainbow fault. In addition, the fault itself contains much irregular crushed ore.

ORE ZONES.

The mine has been divided into nine zones in each of which the veins are concentrated along one or both sides of one of the main north-south faults. From northwest to southeast these zones are designated as follows: No. 9 or Tailings Zone, No. 1 Zone, No. 2 or Rainbow Zone, No. 3 or Sanders Zone, No. 4 or Pinkerton Zone, No. 5 or Butts Zone, No. 6 Zone (Footwall of Goldfinch Fault), No. 7 Zone (Hangingwall of Goldfinch Fault), No. 8 Zone or B. C. Vein. These various zones are indicated in Figure 8.

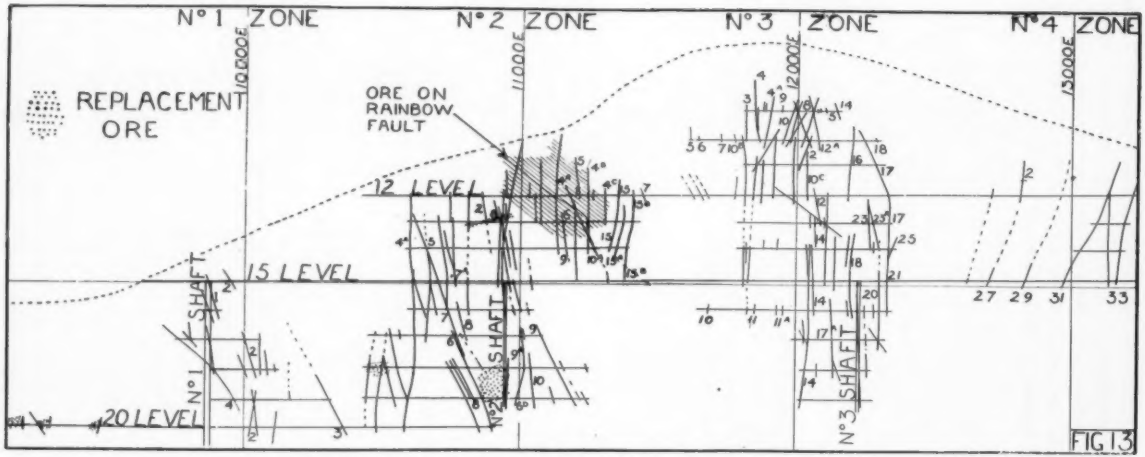


FIG. 13. Projection of ore bodies on a vertical E–W plane.

All the auriferous veins for Zones Nos. 1 to 4 on the 15 level are shown in Figure 3 and the projections of the various ore-bodies in the first five zones on a vertical plane striking east-west (mine) are shown in Figure 13. Here the transverse veins are seen end on and practically vertical. The approximate axes of the diagonal ore-bodies have given in projection an apparent dip to the east.

LIMITATIONS OF THE ORE.

For a given set of conditions such as costs, supply of labor, value of product, etc., there is a limit to the amount of ore available in a mine. On the as-

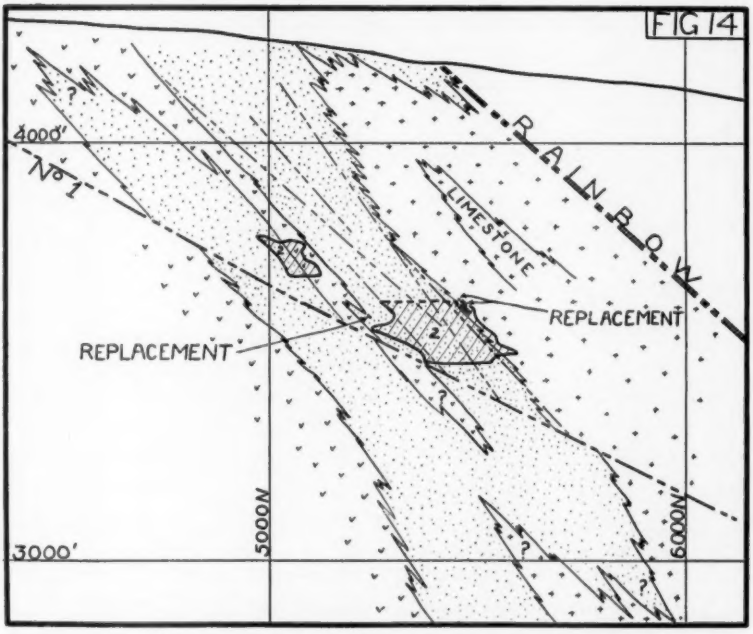


FIG. 14. Longitudinal vertical projection along 10,040 E.

sumption that lateral exploration has been exhaustive the ultimate limit is brought about by the actual bottoming or weakening of the ore-bodies or by extreme depth leading to excessive costs. At the Cariboo Gold Quartz Mine there are numerous small ore-bodies grouped together into the various zones each of which is centered on a north-south fault. The maximum vertical range that has been developed in any one zone is 1,000 feet in No. 3 Zone and the amount of gold both mined and estimated has steadily diminished from 30,000 oz on the top level (10) down to 6,000 oz on the bottom level (18).

A similar decrease on a smaller scale occurs in the No. 4 Zone where the size and grade of the ore-bodies from a better than average grade near the surface (11 level) diminish to non-economic on the 15 level at 400 feet below. In No. 2 Zone however the variation from level to level has been small and the bottom (19) has as much gold per level as the top, namely 30,000 oz. The smaller No. 1 Zone actually shows an increase with depth although further exploration on the upper levels will probably even out the amount to nearly 10,000 oz per level. To illustrate this distribution of the gold the accompanying diagrams have been constructed.

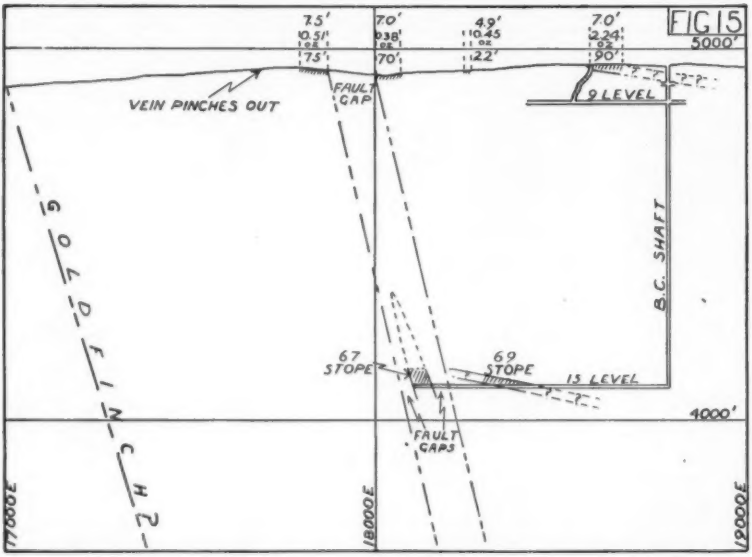
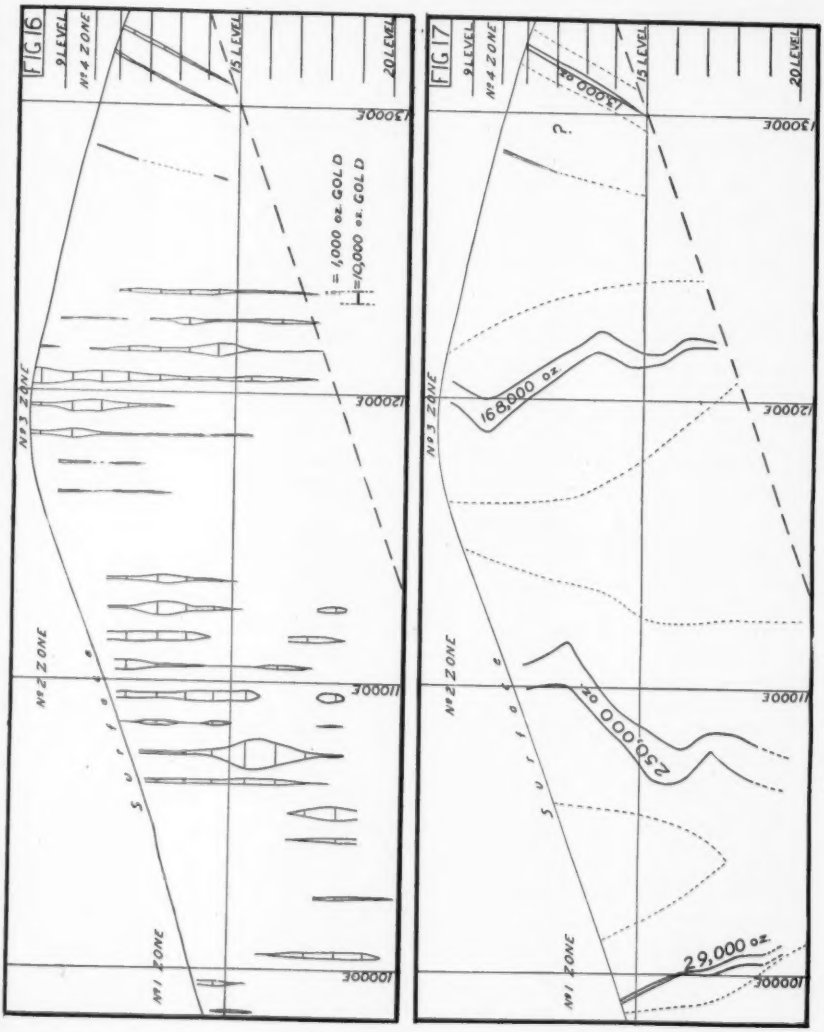


FIG. 15. Diagram of gold distribution on 100 ft vertical coordinate blocks.

In Figure 15 the total amount of gold produced and estimated for each vertical coordinate block 100 feet wide across the mine and between levels is plotted to scale about the centers of each block on a vertical projection. The lines so obtained are joined vertically to show the variation with depth in each vertical slice through the mine.

In Figure 16 these separate strips have been added horizontally for each zone and plotted around the "center of gravity" for each level to show the trend of the zone.

If a line is drawn connecting the lower limit of the ore in No. 3 and No. 4 Zones it is found to have approximately the same direction as the pitch of the drag-fold in the sediments and, as well, of the replacement ore-bodies in Island Mountain Mine (Fig. 8). Actually this "line" is a surface some



FIGS. 16 and 17. Diagrams of gold distribution by zones.

800 feet wide seen edge-on in the projection and it probably has a tilt to the north corresponding to the cleavage. When this "line" or surface is projected still farther and due allowance made for faulting then it puts a limit to No. 1 and No. 2 Zones of another 300 feet below the 20 level and from 500 to 1,000 feet for the ground between No. 1 Zone and the west boundary. It places the limit in Island Mountain Mine at 1,500 to 2,000 feet below the 20 level but in the Mosquito Creek area a vertical range of 3,500 feet is indicated provided an upper limit does not restrict it.

This "line" or surface supposedly limiting the downward extension of the present ore-zone is of course hypothetical but it does fit in with the present known distribution of the ore-bodies and conforms with a structural direction. There is no evidence at present however of an actual structure that would define the position given for this limit. To the east the successive north-south faults step down this theoretical limit but eventually it probably passes entirely above the present land surface. With the present information it is not possible to state if the ore occurring in Williams Creek ground lies above this limit or whether it belongs to a still lower trend of ore-zones.

It is entirely possible that further parallel trends do exist at depth and the completion of the surface mapping at the east end of the property would help to determine whether another one does come to the surface in Williams Creek and could be looked for at depth in the main Cariboo Gold Quartz workings.

ACKNOWLEDGMENTS.

This account is based largely on the detailed geological mapping undertaken since June 1946 by Messrs. W. D. Cameron, M. Guiget and A. C. Skerl, who shared this task in equal amounts.

For mined-out areas the old maps were used to locate faults and veins. This work had been done by the following past members of the staff: Messrs. I. S. Comfort, N. W. Hendry, P. N. Pitcher and F. Richards, to whom acknowledgment is gratefully made. Mr. M. Guiget skilfully drafted most of the various illustrations.

Sincere thanks are tended to Dr. F. C. Buckland, consulting engineer, and Mr. C. D. Stevenson, general manager, for facilitating the investigation, and to Dr. W. B. Burnett, President of the Cariboo Gold Quartz Mining Company, for permission to publish this paper.

CARIBOO GOLD QUARTZ MINING CO., LTD.,
WELLS, B. C.,
June 1, 1948.

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AN UNUSUAL ANTIMONY DEPOSIT IN ARGENTINA.

FEDERICO AHLFELD.

ABSTRACT.

This paper deals with a small group of veinlike replacement deposits in fissures in Pliocene effusive rocks of the Cochinoca area, province of Jujuy, northwestern Argentina. The veins, of near-surface type, contain brecciated and banded ore, chiefly jujuyite, an iron antimonate, and highly antimoniferous opal. The minerals are of colloidal origin. The genesis of the deposit is discussed.

INTRODUCTION.

THE Andean zone of northwestern Argentina contains many widely distributed small size antimony deposits. A few belong to a southern extension of the Bolivian mineral belt of Miocene age and show the characteristics of the Bolivian stibnite veins.[1] In this group is the Puyita Mine vein (Fig. 1) which yielded 300 tons of antimony ore, and is unusual in that it changes in depth to sphalerite. The Pabellón Mine vein, in Ordovician shales, contains rich shoots of cervantite and stibnite near the surface and has yielded 900 tons of stibnite concentrates; from 1937 to 1940 the mine was the largest antimony producer of the country. In depth the lode passes into a gold-quartz vein and stibnite disappears. This type of deposit may be considered as mesothermal, or, perhaps, in accordance with Turneaure,[2] as leptothermal.

Another type includes the small stibnite veins in acid effusive rocks (dacite) of Pliocene age, which occur in many parts of the Puna of Jujuy and in the Sur Lipez province of Bolivia. Here stibnite is associated with chalcedonic quartz. These veins are superficial and of small economic value. The stibnite contains traces of lead and arsenic, but no gold.

THE DONCELLA DEPOSIT.

This deposit is situated at 22°51′ lat. South and 65°59′ long., in the Puna of Jujuy, 50 km SW of Abra Pampa, the central town of the Puna, on the railroad line which extends from Argentina to Bolivia (Figs. 1 and 2).

An extensive volcanic mountain ridge extends from Coranzuli in the west to Casabindo and Doncellas in the southeast and east (Fig. 2). It consists entirely of effusive rocks, mostly large lava flows, which are believed to be of Pliocene age. No craters are visible. On the eastern foot of the ridge are whitish dacite tuffs rich in biotite, and basalt dikes are common. White sandstones of Tertiary age underlie the effusive rocks near Doncellas.

[1] Ahlfeld, Federico, Geología de los yacimientos de antimonio en Bolivia: Mineria Boliviana 3, Nos. 30 and 31, 1946.

[2] Turneaure, F. S., The ore deposits of the eastern Andes of Bolivia: ECON. GEOL., vol. 42, pp. 595–625, 1947.

The effusive rock, probably the basal part of lava flows, is of pinkish to grey color and exhibits fluidal structure. It contains quartz phenocrysts, much biotite, and nearly the same ratio of orthoclase and plagioclase; glass inclusions are common. The lava may be termed a biotite dacite.

The higher parts of the mountain ridge which culminates in the Incahuasi and Sotra peaks (4800 m) are still unknown geologically.

The deposit was found in 1940 by Mr. José Vilaseca who was the first to discover the high antimony content of the ore. He carried on some explora-

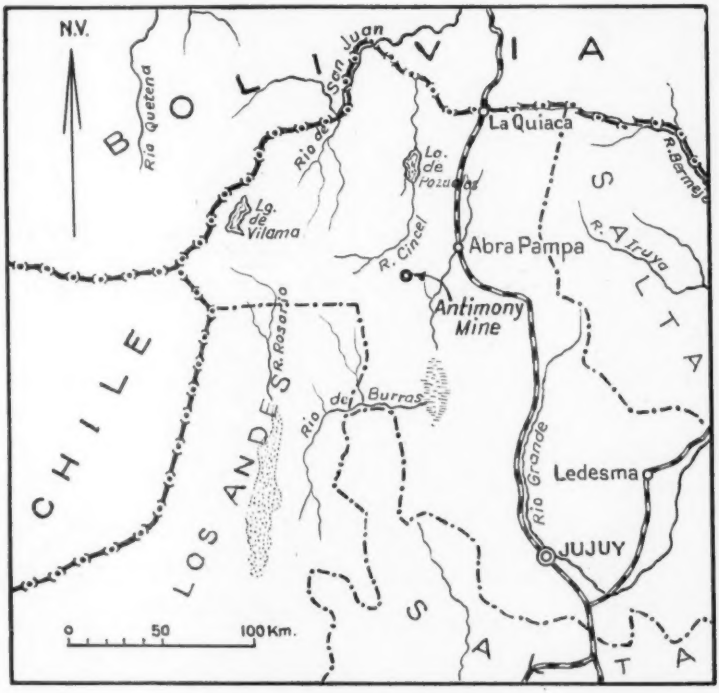

FIG. 1. Index map of antimony mine.

tion and ore testing, which had to be stopped because of the difficulty of separating antimony from iron. Also the deposit seemed to be small.

There are two veins, Nos. I and II. No. I outcrops near a small river bed, 7 km west of the scattered houses of Doncellas, and 3600 m. high. Here a veinlike, although irregular, outcrop is seen for a length of 30 m, covered partly by lava débris. Figure 3 shows across section of the lode as disclosed by a pit 14 m deep. The vein strikes N 60° E and dips 40° NW. The

structure is coarse banded and partly brecciated and the walls are not well defined. Considerable effusive rock, strongly altered to a greenish earthy mass, is mixed with the ore. The brecciated parts also contain fragments of dacite in which the biotite crystals are still preserved. The wall rock shows no traces of silicification or sericitization but it is kaolinized.

The vein filling consists of jujuyite and opal. Jujuyite is probably a new mineral.[3] It forms compact or earthy masses, rather pure or mixed with opal, chalcedony, and remnants of effusive rock. At first it was believed to be

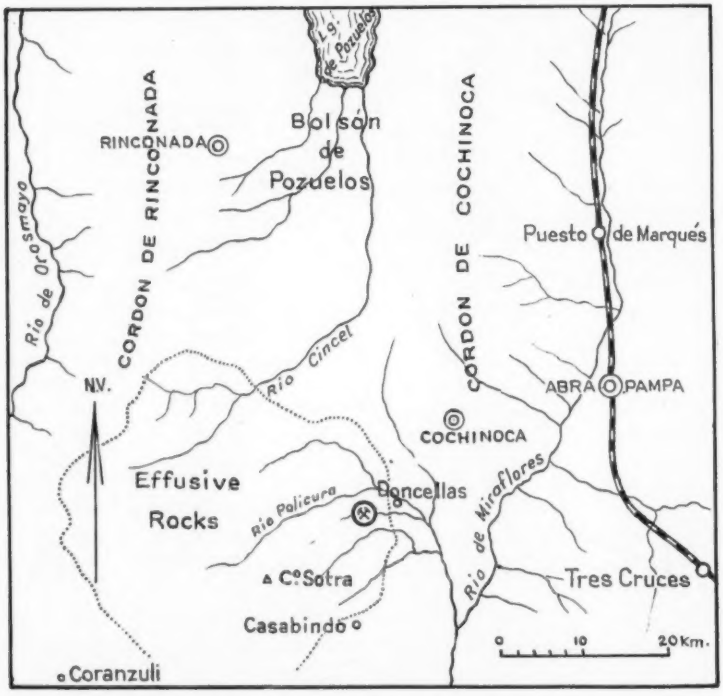

FIG. 2. Sketch of the location of the Doncellas claim.

limonite. It shows a conchoidal fracture and has a dark-brown violet color. The specific gravity of a selected sample was determined to be 4.15 and the density 4.5. Polished sections reveal a colloidal structure. It is microcrystalline, with a weak anisotropism. A sample, carefully selected under the microscope, was analyzed in the laboratory of the Dirección General de Minas

[3] For this new mineral I propose the term "jujuyite," from the province of Jujuy in which it was found.

y Geología, Buenos Aires, and gave the following result:

Fe_2O_3	65.20%
MnO	0.02
Sb_2O_5	18.59
SiO_2	11.70
H_2O	3.40
H_2O (105° C)	0.77
Total	99.68%

No mineral of similar composition is known to the author. I would not venture to suggest a formula because some silica is present as a mechanical mixture in the form of chalcedony, which occupies small vugs in the ore. An average sample of the dump gave 11% Sb.

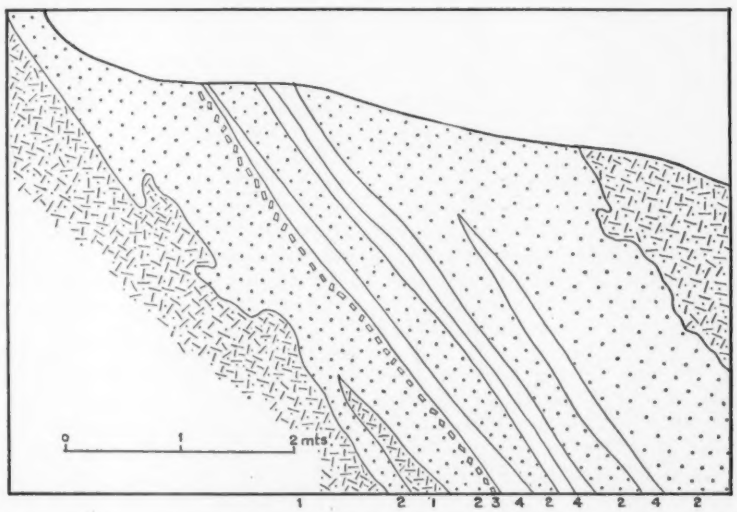

FIG. 3. Cross section of vein No. I, Doncellas. 1. Effusive rock; 2. Jujuyite; 3. Breccia of jujuyite in opal; 4. Opal.

The opal, which forms the central part of the vein and the cement of the breccia, is later than jujuyite. It is of a leatherlike brownish or yellowish color and shows a conchoidal fracture. Under the microscope it proved to be heterogeneous, with inclusions of volcanic glass, and remnants of altered volcanic rock and of jujuyite. Small patches of earthy yellow antimony oxide, probably cervantite, are irregularly distributed in the opal, and presumably are derived from the oxidation of stibnite. In other samples there are no traces of cervantite. The analysis of opal with no cervantite, made in the laboratory of the Dirección General de Minas y Geología, Buenos Aires, gave 15.95% Sb, while Dr. Herzenberg, in Oruro, found 17.9% Sb. To my knowledge, no such highly antimoniferous opal is known to date.

The outcrop of another vein (No. II) is seen in a small river bed, 1 km north of Vein No. I, and with similar characteristics. The vein is 2 m wide and brecciated. Here the jujuyite, associated with red, pinkish and brown opal, is black with a glassy luster. Its specific gravity is 4.7, and its antimony content is higher than in Vein No. I. A selected sample gave 21.63% Sb. The effusive rock of the walls is strongly silicified.

Both veins are irregular replacement deposits along fissures in effusive rocks, and were formed under near-surface conditions by colloidal solutions. In the region there are no traces of thermal springs, but I noticed calcareous tuff terraces 1500 m west of Vein No. I.

These peculiar deposits are probably outcrops of stibnite-quartz veins which are found, as mentioned above, in other parts of the Puna of Jujuy, and related to acid, effusive rocks. 2 km west of Vein No. I, I observed, in another outcrop, jujuyite pockets of white chalcedonic quartz with small radiating needles of stibnite. Probably alkaline ascending thermal waters containing silica-gel, Sb, Fe, and H_2S, intermingled in the upper parts of the veins with acid surface waters, which brought about their oxidation. One should expect to find at depth stibnite-pyrite-quartz veins of normal type.

JUJUY, ARGENTINA,
May 20, 1948.

THE SUPPOSED OXIDATION OF Fe_3O_4 BY CARBON DIOXIDE.

J. E. HAWLEY AND S. C. ROBINSON.

ABSTRACT.

Available thermodynamic data on the reaction $2Fe_3O_4 + CO_2 \rightleftharpoons 3Fe_2O_3 + CO$ are reviewed. Further calculations regarding the equilibrium constant are presented and an approximate evaluation of the ratio of CO_2 to CO at equilibrium is made. From these data the conclusion is reached that oxidation of Fe_3O_4 by CO_2 at temperatures between 200° C and 500° C is possible only when the ratio of CO to CO_2 is less than $1:10^{12}$ and $1:10^7$ respectively. Such ratios indicate that the reaction tends to proceed virtually irreversibly to the left and that, therefore, oxidation of Fe_3O_4 by CO_2 is highly improbable as a process of formation of hematite deposits at or near limestone contacts.

INTRODUCTION

FOR the true explanation of many ore deposits geologists must depend in many cases upon the validity of chemical processes which seem most reasonable and best fit the facts determined by field examination. There is much to be said in favor of setting up multiple hypotheses and writing chemical equations to show in simple form the chemical conditions of deposition of a given mineral, but constant inquiry must be made to insure that such reactions are reasonably correct or at least have not yet been proven thermodynamically improbable or impossible.

The need and value of more precise data on the physical chemistry of minerals and the thermodynamics of reactions involved in their formation is increasingly apparent as evidenced by relatively recent work on the origin of dolomite and magnesite as reviewed by Faust and Callaghan (6),[1] and particularly is this true in regard to the innocuous equation whereby ferroferric oxide has been considered by some writers as being capable of oxidation by carbon dioxide to ferric oxide with the formation of carbon monoxide.

Attention of geologists was drawn to this possibility by B. S. Butler (4) as long ago as 1923 in his suggested explanation of the high ferric oxide content of limestone contact zones. Though this article does not emphasize the actual formation of the mineral hematite (Fe_2O_3) in such zones, but rather the ferric iron content of silicates and unnamed "ferric oxide minerals," it has been quoted in recent years by others, including Gilbert (8), Smitheringale (13) and again in connection with the occurrence of hematite itself in or near limestone formations, at Steep Rock Lake, Ontario, by Roberts and Bartley (12). Indeed in the latter case it forms one of the chief bases on which a theory of origin is founded. In Butler's paper a diagram is reproduced in part from Findlay (7) showing the stability relations of FeO, Fe_3O_4, CO, and CO_2 at various temperatures, a diagram

[1] Numbers in parentheses refer to bibliography at end of paper.

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originally prepared by Baur and Glaessner (1). Though the phase Fe_2O_3 is not included in the equilibria determined for the equation

$$Fe_3O_4 + CO = 3\,FeO + CO_2 \qquad (1)$$

Butler inferred that the *reversal* of this reaction would, if the concentration of CO_2 were sufficient, result in the complete oxidation of FeO through Fe_3O_4 to Fe_2O_3.

On the other hand, Mason (10) in his study of the system FeO—Fe_2O_3 states with regard to the equation

$$2\,Fe_2O_3 + CO = 2\,Fe_3O_4 + CO_2 \qquad (2)$$

"that experimental studies have shown that equilibrium in (this) reaction lies so far to the right that (it) can be considered as *practically irreversible*" (italics are ours).

What, one may ask, is the student of geological processes, struggling to keep abreast of the ever-increasing flow of literature, to do with such conflicting views? Which of the two is correct, or must one fall back on the oft used device of considering that experiment cannot reproduce natural conditions and that almost anything can happen in "geological chemistry"?

The answer is not easily come by. A partial search of the literature, however, does show some interesting data. In the first place one must clearly differentiate between equations (1) and (2) above, since conditions governing equilibria for one do not necessarily apply to the other, regardless of the fact that ferro-ferric oxide (Fe_3O_4) does contain some ferric ions. Secondly, it should also be kept in mind that the physical chemistry of systems including solid and gaseous phases is applicable to such systems, but may not be used directly to infer the behavior of the same substances in the liquid and gaseous states.

Fe_3O_4—FeO EQUILIBRIA.

In his studies on iron oxide reduction equilibria Ralston (11), rather startlingly, in view of subsequent geological papers, calls attention to the early work of Baur and Glaessner and "their *famous incorrect* diagram, which has entered so many text books on metallurgy . . .," and we may add, on geology, and that

> over the range of 700° C–950° C their equilibrium gas compositions were in reasonable agreement with more recent work. (But) at the lower temperatures they were completely in error, and in both cases (Fe_3O_4/FeO and FeO/Fe) their curves turned in the wrong direction.

It was the lower temperature range, specifically 490° C, we may note, to which Butler called attention as the temperature most favorable for reaction (1) to move to the left, regardless of pressure, given the proper concentration of CO_2:CO.

The more correct diagram of the equilibria between the oxides of carbon and iron, as given by Ralston, is reproduced in part in Figure 1. Unfortunately the data in this do not extend below a temperature of 550° C,

though other diagrams after Eastman (reproduced by Ralston) show that between temperatures of 416° C and 600° C metallic iron may be directly oxidized to magnetite (Fe_3O_4) with the proper concentration of CO and CO_2 without the formation of FeO.

Above about 600° C, Figure 1, FeO is the stable oxide when in contact with gases consisting of something over 40 percent carbon monoxide (60% carbon dioxide) but at still higher temperatures less carbon monoxide is required to reduce Fe_3O_4 to FeO (Curve 1) or more carbon dioxide is necessary to oxidize FeO to Fe_3O_4.

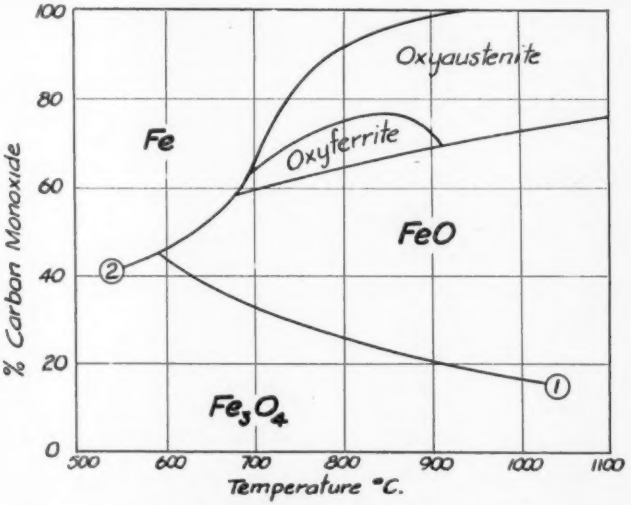

FIG. 1. Equilibria between oxides of carbon and iron.

In any case the errors noted by Ralston in the Baur-Glaessner diagram do not alter the general conclusion used by Butler that in the presence of the proper mixture of CO and CO_2 magnetite (Fe_3O_4) is the stable phase instead of ferrous oxide or iron at temperatures between 400 and 600° C, to the correctness of which the many magnetite deposits in or near limestone contacts bear ample testimony.

Fe_2O_3—Fe_3O_4 EQUILIBRIUM WITH OXIDES OF CARBON.

It was particularly in the next step of Butler's reasoning that a more serious error was involved, namely in assuming that since carbon dioxide even in the presence of considerable carbon monoxide will oxidize iron or ferrous oxide to Fe_3O_4, given still larger amounts of CO_2, oxidation will be carried a step further to completion with the formation of Fe_2O_3.

In this connection Ralston (11, p. 305) notes:

In none of the diagrams . . . has a stability field for Fe_2O_3 been plotted. For practical purposes the reduction of ferric oxide to magnetite by carbon monoxide (or hydrogen) (equation 2) is considered *irreversible*, since the equilibrium mixture of gases contain only, say 1 part of (hydrogen or) carbon monoxide per million. The line separating the ferric oxide field is therefore practically coincident with the horizontal axis of the coordinates (Fig. 1) and so closely spaced to it that it cannot be shown graphically.

The general acceptance of the irreversibility of this reaction is also shown by Davis (5) in his discussion of the reduction of hematite to magnetite by either carbon monoxide or hydrogen where he states:

The reactions that produce magnetite from hematite are *practically irreversible*—that is, neither CO_2 nor water will oxidize magnetite appreciably at temperature used in magnetic roasting (800° F–1200° F).

The citation of Mason at a later date is in agreement with this, though none of the above writers give the precise thermodynamic data and calculations on which their statements were based. An attempt to provide such calculations is presented here. Search of available literature for the necessary data has revealed that differences in the published values for such functions as the heat of formation (ΔH) of Fe_2O_3 are sufficiently great to affect materially the order of magnitude of the equilibrium constant. The effects of such discrepancies will be discussed later.

Bray (2) has published calculated values for the free energy (ΔF) and the equilibrium constant (K) for the reaction (2) proceeding to the left at temperatures of 25° C and 700° C. His values for the reaction, $\Delta F_{25°\,C} = 9{,}010$ calories and $\Delta F_{700°\,C} = -5{,}840$ calories, when inserted in the equation $\Delta F = -RT \ln K$ (where R is the gas constant = 1.985 and T the temperature of reaction in degrees absolute), yield values of $K_{25°\,C} = 10^{6.55}$ and $K_{700°\,C} = 20$. Negative values of ΔF substituted in this equation must result in values of K in excess of unity and thus the reaction will tend to proceed from right to left (*i.e.* towards Fe_3O_4) at both temperatures.

If the products of the activities of substances on the left, divided by the products of the activities of substances on the right, be substituted for

$$K, \left(K = \frac{(a_{Fe_3O_4})^2 \cdot a_{CO_2}}{(a_{Fe_2O_3})^3 \cdot a_{CO}} \right),$$

and further, if the approximation that activities of solid crystalline substances are equal to unity be made, K becomes equal to $\frac{a_{CO_2}}{a_{CO}}$. The further approximation that partial pressures are substantially equivalent to activities of the two gases permits an approximate evaluation of the concentrations of the two gases at equilibrium. Thus if at 25° C,

$$K = \frac{P_{CO_2}}{P_{CO}} = 10^{6.55},$$

the ratio of CO_2 to CO necessary to force the reaction to proceed to the right (*i.e.* to effect oxidation of Fe_3O_4 to Fe_2O_3 by action of CO_2) must be in

excess of one million to one. At 700° C this ratio is reduced to twenty to one, an exceptionally low ratio compared with that derived in calculations which follow. Furthermore, even with a ratio as low as 20:1, oxidation of Fe_3O_4 by CO_2 is thermodynamically improbable.

The postulated temperature for this reaction in natural deposition of iron oxides ranges from zero to 500° C. In order to evaluate the reaction in this range values of ΔF of formation of Fe_2O_3 and Fe_3O_4 compiled by Ralston (11) were used, together with values of ΔF for CO and CO_2 calculated from other data. ΔF of reaction to the left is equal to the sum of ΔF's of the substances on the left minus the sum of ΔF's of the substances on the right. At 25° C

$$2\,Fe_3O_4 + CO_2 = 3\,Fe_2O_3 + CO$$

ΔF reaction to the left

$$= [2(-241{,}550) + (-94{,}260)] - [3(-173{,}050) + (-32{,}510)]$$
$$= -25{,}700.$$

This value is then substituted as described above to obtain values for K_{reaction} and the ratio $\frac{P_{CO}}{P_{CO_2}}$. The data used and calculated are presented in Table I.

TABLE I.

Temp.° C	ΔF_{CO}	ΔF_{CO_2}	$\Delta F_{Fe_2O_3}$	$\Delta F_{Fe_3O_4}$	ΔFreaction to the left	K	$\frac{P_{CO}}{P_{CO_2}}$
25° C	−32,510	−94,260	−173,050	−241,550	−25,700	$10^{18.9}$	$10^{-18.9}$
100° C	−34,040	−94,400	−168,380	−235,415	−26,050	$10^{15.3}$	$10^{-15.3}$
200° C	−36,170	−94,590	−162,192	−227,800	−27,440	$10^{12.7}$	$10^{-12.7}$
300° C	−38,280	−94,750	−156,230	−220,100	−27,980	$10^{10.7}$	$10^{-10.7}$
400° C	−40,440	−94,900	−150,688	−212,980	−28,360	$10^{9.2}$	$10^{-9.2}$
500° C	−42,870	−95,060	−145,450	−205,610	−27,060	$10^{7.7}$	$10^{-7.7}$

It is at once apparent that the value of $\Delta F_{\text{reaction}}$ at 25° C in the above table, (− 25,700), differs greatly from Bray's value of − 9,010. This difference is almost wholly due to differences in values of $\Delta H_{25°\,C}$ of Fe_2O_3 used in the two sets of calculations.[2] Despite so great a difference, its

[2] Some values of $\Delta H_{25°\,C}$ for Fe_2O_3 are:

− 198,500 calories per mol (Roth, quoted by Bichowski and Rossini, 1936).
− 192,200 calories per mol (Ralston, 1929).
− 190,700 calories per mol (Handbook of Physics and Chemistry, 1947).

Values of $\Delta H_{25°\,C}$ for Fe_3O_4, CO and CO_2 as listed in the Handbook of Physics and Chemistry (1947) agree closely with those published elsewhere; using these values and two of the above figures for $\Delta H_{25°\,C}$ of Fe_2O_3, the following values of ΔH for reaction to the left are obtained.

$$2Fe_3O_4 + CO_2 \rightleftharpoons 3Fe_2O_3 + CO$$

$$\Delta H = [(2 - 266{,}910) + (-94{,}385)] - [3(-198{,}500) + (-26{,}428) = -6{,}277 \quad (1)$$

or

$$\Delta H = [2(-266{,}910) + (-94{,}385)] - [3(-192{,}200) + (-26{,}428) = -25{,}177 \quad (2)$$

effect within the temperature range from 25° C to 500° C does not materially affect the possibility of oxidizing Fe_3O_4 by the action of CO_2. At 25° C, if Bray's figures be used, the ratio of CO to CO_2 at equilibrium is $1:10^{6.55}$; by the figures in Table I this ratio is $1:10^{18.9}$. Further it is apparent also that although in the above table the ratio is reduced to $1:10^{7.7}$ at 500° C and, according to Bray, to 1:20 at 700° C, oxidation of Fe_3O_4 by CO_2 at temperatures which may be reasonably expected under natural conditions is thermodynamically improbable.[3]

In order to interpret what is meant by these figures, the minimum ratio of P_{CO_2}/P_{CO}, that of Bray for equilibrium at 700° C, is taken as the example. Since at equilibrium there must be 20 parts of CO_2 present for every part of CO, for the reaction to proceed to the right (*i.e.* for oxidation of Fe_3O_4 to Fe_2O_3) there must be more than 20 parts of CO_2 to each part of CO. If there are less than 20 parts of CO_2 per part of CO the reaction will proceed to the left with consequent reduction of Fe_2O_3 to Fe_3O_4 by action of CO. However, since by the stoichiometric equation, one mol of CO would be generated for every mol of CO_2 used up in oxidation of 2 mols of Fe_3O_4 (granting conditions were such that this could occur), it is at once obvious that an unlimited supply of CO_2 must be coupled with a means of effective removal of virtually all CO generated, in order that the oxidation reaction could proceed. Geologically, this would require a very open system and unlimited supplies of CO_2. Wherever structural conditions interfered with the requirements of an open system, it is almost certain that the equilibrium would be reached as the CO concentration rose and subsequent reduction of Fe_2O_3 would occur. It is indeed difficult to imagine natural conditions in which the necessary ratio of CO_2 to CO at equilibrium could be either reached or maintained.

The effect of containing pressures on equilibrium is probably not significant since the equation requires one mol of gas on either side.

Finally, in considering the above data with regard to natural occurrences, we are only on safe ground as long as this is applied to solid magnetite or hematite in contact with gases. No attempt has been made here to predict the effect of CO_2 and CO on iron oxides in the liquid state, nor on iron in the form of volatile chlorides or other gaseous compounds.

Using figures compiled by Kelley (1941) for entropies of the four compounds ΔS for the reaction to the left may be computed.

$$2Fe_2O_4 + CO_2 \rightleftharpoons 3Fe_2O_3 + CO$$
$$S_{[3(36.0)+51.09]-[2(31.5)+47.31]} = 9.3.$$

Substituting these values in the equation $\Delta F = \Delta H - T\Delta S$,

$$\Delta F = -\ 6{,}277 - (9.3)(298) = -\ 9{,}050 \qquad (1)$$

$$\Delta F = -\ 25{,}177 - (9.3)(298) = -\ 27{,}950 \qquad (2)$$

[3] It is obvious that the two parallel sets of values for ΔF reaction and thus of K at various temperatures depend basically on the original values of the heat of formation (ΔH) of Fe_2O_3 which were used in each set. The more complete set of values of ΔF of reaction in Table I indicate that the maximum negative values are attained at about 400° C and that they decrease at higher temperatures. By analogy, therefore, it may be inferred that Bray's value of $\Delta F_{700°\,C}$ and his value of $K_{700°\,C}$ are the lowest values in the temperature range between 0° C and 700° C. In other words, oxidation of Fe_3O_4 to Fe_2O_3 by CO_2 while thermodynamically improbable at 700° C is even less probable at lower temperatures.

CONCLUSIONS.

Examination of reactions by which ferrous iron is oxidized by CO_2 in the presence of CO to Fe_3O_4 and the supposed further oxidation of Fe_3O_4 by CO_2 has shown that though the original data on the first reaction by Baur and Glaessner were not entirely correct, magnetite is the stable phase between 400° and 600° C with the proper concentration of CO and CO_2. The assumption that the further reaction $2\,Fe_3O_4 + CO_2 \rightleftharpoons 3\,Fe_2O_3 + CO$ will take place to the right is shown both by a review of opinions of others and by thermodynamic calculations to be most improbable, even when the lowest equilibrium constant at 700° C is used. Present data on heat of formation of Fe_2O_3 suggest that this equilibrium constant should be considerably higher and that between temperatures of 200° C and 500° C the ratio of CO to CO_2 at equilibrium is of the order $1:10^{12}$ and $1:10^{7}$. The formation of hematite instead of magnetite in the vicinity of limestone contacts by the oxidation of magnetite by carbon dioxide liberated from the limestone would thus appear extremely unlikely.

The writers are indebted to Dr. N. L. Bowen and Dr. Sahama of the Geophysical Laboratory for a critical reading of the paper.

QUEEN'S UNIVERSITY,
KINGSTON, ONTARIO,
May 27, 1948.

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REVIEWS

A History of the Petroleum Administration for War. 1941–1945. Prepared under direction of JOHN W. FREY AND H. CHANDLER IDE. Pp. 463; figs., charts, 11 appendices. U. S. Government Printing Office, Washington, D. C., 1948. Price, $3.00 (cloth).

It is a commendable undertaking to bring together in one interesting volume the vast amount of material accumulated by the P.A.W. during wartime. It is partly narrative and partly reports.

The book deals with the dark problems faced in the early war years and with the development, mobilization, organization, programming and relation to other bureaus both in the United States and abroad. It shows the steps that had to be taken to meet civilian and war demands—revising and increasing transportation and distribution. It deals with new and expanded methods of production and refining and of synthetic rubber development. It treats extensively of foreign supplies, allocations, and refining and foreign relations, and oil policy. Many charts illustrate the text. Eleven appendices cover details and projects.

Human Geography, an Ecological Study of Society. By C. LANGDON WHITE AND GEORGE T. RENNER. Pp. 692; figs. 437. Appleton-Century-Crofts, Inc., New York, 1948. Price, $6.00.

Following their definition of geography "as the study of human society in relation to the earth background" the authors proceed to develop the physical features that influence society, then the social data drawn from the realm of human affairs, and the abstract relations between the two.

Part 1 of the book is an introduction. Part 2 deals with the various types of climate; Part 3, the Biotic factors; Part 4, Physiographic factors; Part 5, Soil factors; Part 6, Mineral factors; Part 7, Hydrographic; Part 8, Spatial factors (shape, size, location); Part 9, Social factors; Part 10, Geographical theory. Social and industrial life are included under each type of climate covered in Part 2.

The book is delightfully written and excellently illustrated. One leafs it over with the same interest as the *National Geographic*.

This is one of the most interesting geographies that has appeared in years.

Popular Gemology. By RICHARD M. PEARL. Pp. 316; figs. 115. John Wiley and Sons. New York, 1948. Price, $4.00.

This semi-technical book is presented in popular language for the benefit of gemologists, the lover of gems, the collector, the jeweller and the lapidary. It is well written, nicely indexed, and contains many illustrations. Its 8 chapters cover the lure of gems, recognition, faceted gems, cabochon and carved gems, silica gems, gems with a genealogy, man-made gems and luminescent gems. The subject matter follows Dana's classification and covers locality, occurrence, methods of production, and recent commercial developments. Of particular interest are

the parts dealing with fluorescence and the silica gems. Any reader or student of gem stones will find this book of interest.

Soil Mechanics in Engineering Practice. By KARL TERZAGHI AND RALPH B. PECK. Pp. 566; figs. 218. John Wiley & Sons, New York, 1948. Price, $5.50.

This fundamentally theoretical and practical discussion of soil mechanics gives information regarding the knowledge and understanding of the problems of soil mechanics so necessary to earthquake engineers.

Its three parts divide the subject matter naturally: Part A, Physical Properties of Soils; Part B, Theories of Soil Mechanics; and Part C, Problems of Design and Construction.

Part A covers the index properties of soils, their hydraulic and mechanical properties, and the drainage of soils.

Part B covers plastic equilibrium in soils, settlement and contact pressure, and the hydraulics of soils.

Part C deals with soil exploration, earth pressure and stability of soils, foundations, settlement due to exceptional causes, and miscellaneous problems of design and construction.

Those who are acquainted with Professor Terzaghi's writings will realize how fundamental and thorough the subject matter is covered. The subject matter includes material of interest not only to civil engineers but much of value to the geologist, such as all three chapters of Part A, and the hydraulics of soils. Moreover, the engineering geologist will profit greatly from the engineering information contained in Part C.

A. M. B.

From the Ground Up. By PAUL M. TYLER. Pp. 248; figs. 83. McGraw-Hill Co., New York, 1948. Price, $3.50.

This title is meant to indicate what happens with metals and minerals after they leave the ground, since it deals with the facts and problems of the mineral industries of the United States. It is a new approach to the subject of mineral economics and presents a picture of the full economic development and prudent employment of natural resources and the ways in which they affect the welfare of the nation.

Mr. Tyler's rich background in the Bureau of Mines, in the Foreign Economic Administration, and as consulting mineral technologist and economist has provided an excellent basis for the subject matter covered in this volume. Although dominantly factual, several chapters offer proposals for improving conditions in the mineral industry in keeping with the natural industry. The various chapter headings give an idea of the contents: The Role of Minerals in Our American Economy; High Lights of a Great Industry; Production and Consumption; Wages Up, Prices Down; The Miners Need Tools; Our Energy Supply; Common Metals; Minor Metals; Industrial Minerals; Some Fallacies and Misconceptions about Mining; Factors Influencing Future Trends; National Policies Dealing with Minerals.

The book contains a lot of valuable statistical information and much material of interest to all geologists, mining engineers, mineral economists and geographers.

A. M. B.

BOOKS RECEIVED

M. L. MIGNONE.

U. S. Department of the Interior—Bureau of Mines. April–June 1948.

Rept. Inv. 4221. Stone Hill Copper Mine, Cleburne and Randolph Counties, Ala. HUGH D. PALLISTER AND J. R. THOENEN. Pp. 29; figs. 6; tbls. 15. *Detailed log of cores in different holes. Primary sulfides assayed 0.05 to 3.30% copper.*

Rept. Inv. 4237. West Pinos Altos Zinc-Lead Deposits, Grant County, N. Mex. JOHN H. SOULÉ. Pp. 8; figs. 5; tbls. 2. *Most important are sulfide ores of lead-zinc with carbonate and silica gangue; major economic mineral is marmatite, iron-rich sphalerite. Development by shaft about 100 feet deep.*

Rept. Inv. 4241. North Carolina Mica Spots, Mitchell, Macon, Gaston, and Yancey Counties. L. A. DAHNERS AND F. K. MCINTOSH. Pp. 16; figs. 10. *Property and access, history and production, physical features, description of deposit, ore, mine workings and present plant installation of four mines.*

Inf. Circ. 7448. Mining Methods of the Holden Mine, Howe Sound Co., Chelan Division, Holden, Wash. R. L. SODERBERG. Pp. 27; tbls. 5; figs. 24. *Powder-blast method produced 3,371,701 tons of broken ore but shattered the walls causing dilution and damage. Subsequently diamond-drill blast-hole mining was used (1) by vertical ring drilling from drifts (2) by horizontal ring drilling from raises or flat-hole system.*

Inf. Circ. 7452. Blast-hole Drilling with Diamond Drills at the Tennessee Copper Co. Mines, Ducktown, Tenn. WILLIAM A. BECK. Pp. 17; tbls. 12; figs. 7. *Rocks are lower Cambrian, part of the Great Smoky formation; ore is massive sulfide (75 percent +). The method has passed experimental stage.*

Inf. Circ. 7458. Transportation of Iron Ore, Open-cut Mines, Lake Superior District. JOHN A. JOHNSON AND FRANK E. CASH. Pp. 24; figs. 16. *Trucks and belt conveyors have replaced rail haulage; electrically operated shovels predominate; belt conveyors carry 500 to 1,200 tons per hour at speeds between 300 to 550 ft per minute; longest belt, 1,750 ft, 8 1/3° steepest inclination.*

Geophysical Abstracts 131, October–December 1947. V. L. SKITSKY. Pp. 86. U. S. Geological Survey Bull. 957-D, Washington, D. C., 1948. *Classified by methods, unclassified geophysical and related nongeophysical subjects, patents, index.*

Illinois Geological Survey.

Rept. Inv. 127. Illinois Mineral Industry in 1946. WALTER H. VOSKUIL. Pp. 123; figs. 21; tbls. 85. Urbana, 1947. *Detailed review of principal minerals.*

Rept. Inv. 129. Physiographic Divisions of Illinois. M. M. LEIGHTON, GEORGE E. EKBLAW AND LELAND HORBERG. Urbana, 1948. Pp. 18; figs. 4. *Minor modifications in Fenneman's divisions proposed; description of boundaries and characteristic features of subdivisions; discussion of their origin and relations to glacial features and bedrock topography.*

Illinois Geological Survey. Urbana, 1948.

Circ. 143. Mineral Resource Research, 1946–1947, by the Illinois State Geological Survey. M. M. LEIGHTON. Pp. 16; photos 23; charts and maps. *Coal, oil and gas, clays, rock and rock products, fluorspar, zinc and lead, groundwater resources, engineering geology and mineral economics. Reprint from Chief's annual report to Director.*

Circ. 144. Some Chester Outcrop and Subsurface Sections in Southeastern Illinois. ELWOOD ATHERTON. Pp. 10; figs. 8. *Electric logs of several formations.* **Unusual Oolite Grains from the Ste. Genevieve Limestone.** RAYMOND S. SHRODE. Pp. 5; figs. 6. *Description of figures; no attempt to interpret origin of grains or significance in relation to mode of formation.*

Suppl. to Bull. 62. Analyses of Illinois Coals. GILBERT H. CADY. Pp. 77; tbls. 6; fig. 1. *Analyses of face samples of Illinois coals since 1935 with additions to and revision of data in Bulletin 62 and revised mine and county averages.*

Limestones and Dolomites in the St. Louis Area. NORMAN S. HINCHEY, R. B. FISCHER AND W. A. CALHOUN. Pp. 80; figs. 2; pls. 4. Missouri Geological Survey Rept. Inv. 5. Rolla, 1947. *Analyses of 270 samples from 17 localities; Ordovician and Mississippian.*

Sedimentation of Reservoirs in Ohio. EARL E. SANDERSON. Pp. 27; pls. 8; tbls. 4; photos, 8. Ohio Water Resources Board Bull. 17. Columbus, 1948. *Sedimentation surveys of various Ohio reservoirs.*

Geology and Mineral Deposits of Bumpass Cove, Unicoi and Washington Counties, Tennessee. JOHN RODGERS. Pp. 82; figs. 5; tbls. 10; photo, 1; pls. 5 (in pocket). Tennessee Division of Geology, Bull. 54. Nashville, 1948. *500′ of lower Cambrian Shady dolomite underlie Bumpass Cove with zinc, lead and iron sulphides; oxidized deposits of zinc, lead, iron, and manganese in residual clay of weathered dolomite. To end of 1946 production of concentrates was 493,318 long tons Fe, 213,286 short tons Zn, 29,652 short tons Pb, and 29,162 long tons Mn. Larger oxidized ore bodies are mined out.*

Technical Publications, Year 1946. STANDARD OIL CO. (N. J.) AND AFFILIATED COMPANIES. Pp. 356; figs. 86; tbls. 71; photos, 15; chart, 1. New York, 1947. *23 articles on various research and development problems of petroleum technology; each article preceded by photograph and short biography of authors.*

Part of Northwest Quarter of Beauchastel Township, Rouyn-Noranda County. W. G. ROBINSON. Pp. 19; tbl. 1; 1 colored map 24½″ × 23½″, scale 1″ = 800′. Quebec Department of Mines, Geol. Rept. 30. Quebec, 1948. *General, structural, and economic geology; no commercial deposits of gold or other metals developed.*

Annual Report of the Swaziland Geological Survey for 1944. Pp. 26; figs. 7; tbls. 2. Morija, 1945. *Relation of work and program.*

Relatório de 1946. CONSELHO NACIONAL DO PETRÓLEO. Pp. 308; figs. 28; numerous tables and charts. Rio de Janeiro, 1948. *Detailed petroleum work and program in the Maranhao, Piaui, Sergipe and Bahia states.*

British Department of Scientific and Industrial Research—Regional Geology. London, 1948.

South-West England. 2nd Edit. HENRY DEWEY. Pp. 72; figs. 20; pls. 12. *Study of various rocks and mines.*

The Pennines and Adjacent Areas. 2nd Edit. D. A. WRAY. Pp. 87; figs. 28; pls. 11. *Rocks, systems and economic products.*

East Yorkshire and Lincolnshire. VERNON WILSON. Pp. 94; figs. 34; pls. 8. *2 of most important iron-producing deposits of Britain; oolitic clay iron-stone with up to 37% Fe.*

North Wales. 2nd Edit. BERNARD SMITH AND T. NEVILLE GEORGE. Pp. 89; figs. 32; pls. 12. *General geology.*

Bristol and Gloucester District. 2nd Edit. F. B. A. WELCH, R. CROOKALL AND G. A. KELLAWAY. Pp. 99; figs. 24; pls. 12. *Structural and economic geology; iron, lead and zinc practically exhausted.*

South Wales. 2nd Edit. J. PRINGLE AND T. NEVILLE GEORGE. Pp. 10; figs. 29; pls. 8. *Various systems and rocks; pleistocene and recent deposits.*

The Wealden District. 2nd Edit. F. H. EDMUNDS. Pp. 93; figs. 21; pls. 13. *Very important water supply; 45,000 tons a week of coal in 1938; iron and building materials also present.*

Edinburgh, 1948.

The Midland Valley of Scotland. 2nd Edit. M. MACGREGOR AND A. G. MACGREGOR. Pp. 95; figs. 16; pls. 8. *General and glacial geology.*

Scotland: The Tertiary Volcanic Districts. 2nd Edit. J. E. RICHEY. Pp. 105; figs. 57; pls. 9. *Rocks of various periods; few materials of industrial value.*

The Grampian Highlands. 2nd Edit. H. H. READ AND A. G. MACGREGOR. Pp. 83; figs. 23; pls. 11. *General and economic geology; numerous minerals.*

Scotland: The Northern Highlands. 2nd Edit. J. PHEMISTER. Pp. 94; figs. 27; pls. 8. *Only valuable metallic ores were galena, now abandoned; various non-metallic rocks and minerals, mineral waters and construction materials.*

Upper Cambrian and Lower Ordovician Rocks in Kansas. RAYMOND P. KEROHER AND JEWELL J. KIRBY. Pp. 140; pls. 6; figs. 13. Kansas Geological Survey; University of Kansas Publications Bull. 72, 1948. *Methods of study; description and correlation of subdivisions; geologic cross sections; no detailed discussion of broadly regional tectonic features.*

North Mississippi Floods of February 1948. DISTRICT OFFICE, WATER RESOURCES BRANCH, U. S. GEOLOGICAL SURVEY UNDER DIRECTION OF IRVING E. ANDERSON. University, 1948. Pp. 55; figs. 7; pls. 3. *General description of storm and flood; stages and discharges at river-measurement stations during flood; two storage reservoirs in operation.*

Zones of Plattin-Joachim of Eastern Missouri. JOHN G. GROHSKOPF. Pp. 15; figs. 5; tbl. 1. Missouri Geological Survey and Water Resources Rept. Inv. 6. Rolla, 1948. Reprint from A.A.P.G. Bull. vol. 32, No. 3, March 1948. *Stratigraphy; zoning based upon lithology and insoluble residues.*

Ontario Department of Mines. June–July 1948.

Prel. Rept. 1948–5. Preliminary Report on the Geology of McElroy Township, District of Timiskaming. E. M. ABRAHAM. Pp. 4; map, scale 1″ = ½ mile. *General, structural and economic geology; gold chief mineral.*

Prel. Rept. 1948–6. Showings in the Vicinity of Oneman Lake, District of Kenora. ROBERT THOMSON. Pp. 4; figs. 2. *History, physical conditions, general and economic geology; prospection for zinc and gold; arsenopyrite most abundant metallic mineral (up to 35%).*

Prel. Rept. 1948–7. Report on Mosher Discovery of Radioactive Mineral, Pitt Township, District of Cochrane. NELSON HOGG. Pp. 10; fig. 1. *Paleozoic and Precambrian formations; most important source of radioactivity is carbonate vein, of probably impure dolomite, 6″ to 2 ft wide; no commercial development yet; 3 samples tested returned U_3O_8 equivalents of 0.03, 0.12 and 0.055%.*

French Equatorial Africa Bull. 3. Paris, 1947. **Exploration de la Partie Méridionale des Plateaux Batékés.** V. BABET. Pp. 37; figs. 10; pls. 13. *Physical description; geologic study by regions and by formations; short geologic history.* **Introduction à l'Etude des Sols de l'Afrique Equatoriale Française—Sur les Caractères Physiques Généraux des Sols en Rapport avec la Rochemère.** V. BABET. Pp. 16; chart. *Specific characters of various soils according to geologic nature of ground and conditions of two factors, relief and vegetation.*

Boletín de la Escuela Nacional de Ingenieros. Serie 3, T XX, Lima, Peru, 1947. **La Mecánica de Suelos en la Ingeniería Moderna (Soil Mechanics in Modern Engineering.)** L. SOLDI LE BIHAN. Pp. 11. **Nomenclatura Mineralógica y Glosario de Términos Mineros (Mineralogical Nomenclature and Glossary of Mining Terms).** GIL RIVERA PLAZA. Pp. 55.

Estudos, Notas e Trabalhos do Serviço de Fomento Mineiro. Portugal, 1947. Pp. 103; numerous figures, plates, maps, tables. *Six papers by various authors on: geology and genesis of the Portuguese chromite deposits; platinum in the district of Bragança; study of the genesis of the Montemor-o-Novo iron deposit; the methods employed by a Swedish firm in the magnetic highs in Portugal; reconnaissance plans in the iron and manganese mine of Serra do Rosalgar; résumé of activities of Mining Service during first semester of 1947.*

Subsídios para o Estudo dos Depósitos da Orla Meso-cenozóica Occidental de Portugal. G. SOARES DE CARVALHO. In 3 pamphlets; pp. 48; figs. 8. Coimbra, 1947–48. *Stratigraphic value of plant fossils of Quinta do Peneireiro; sedimentary deposits with manganese in Anadia region; copper in the Mesozoic deposit around Coimbra.*

Progress Report of the Swaziland Geological Survey Department, 1945 and 1946. Pp. 36; map 1; figs. 6; tbls. 4. Durban, 1948. *Report of geologic activities.*

Annual Report of the Uganda Geological Survey Department for 1946. Pp. 37; tbls. 3. Entebbe, 1948. *Field and headquarters work; water supply.*

Minerales. Pp. 51; figs. 25. Inst. ing. Chile Rev., no. 25, 3rd year, Santiago de Chile, June 1948. *4 papers, contribution to the geology of the Concepcion Bay; electrification in coal mines; ventilation in coal mines; method of beneficiation of sulphur "caliche" by autoclave.*

SCIENTIFIC NOTES AND NEWS

CHAS. H. BEHRE, JR., Professor of Economic Geology, Columbia University, has been granted a year's leave of absence in 1948–49 to continue the study, begun two years ago, of the genesis, distribution, and geologic control of the mineral deposits of Mexico. During Professor Behre's absence two specialists in the same field have accepted invitations to lecture in the Department of Geology, with special emphasis on ore genesis and its influence on minerals search—Dr. T. S. Lovering of the U. S. Geological Survey in October and Dr. Donald M. Davidson, Consulting Geologist, of the E. J. Longyear Co., in November.

LT. COL. HUBERT G. SCHENCK, Chief of the Natural Resources Section, General Headquarters, Supreme Commander for the Allied Powers, and SHERMAN K. NEUSCHEL (U.S.G.S.), Chief of the Pacific Geological Surveys, Engineer Office, General Headquarters, Far East Command, represented General Douglas MacArthur at the 18th International Geological Congress in London.

CHAS. CAMSELL, past President of the Canadian Institute of Mining and Metallurgy, received from Lord Rennell of Rodd, President of the Royal Geographical Society, the Founder's Medal of that Society, which had been awarded him in 1946 "for his contribution to the geology and geography of Canada and his work in advancing geographical science in the Dominion."

W. J. LORING, mining engineer of Tonopah, Nev., received from the A.I.M.E. a gold pin and certificate placing him in "Legion of Honor" status upon his completion of 50 years of active service in the mining engineering profession.

G. M. FURNIVAL has resigned as director of mines for Manitoba to take a position with the Standard Oil Co. of California, with which he was associated before joining the civil service of Manitoba.

ALEXANDER N. WINCHELL has resigned after three years as resident consultant at the Stamford Research Laboratories of the American Cyanamid Co. He will renew his activities as a consulting geologist and crystallographer from his new headquarters at 88 Vineyard Road, New Haven, Conn.

R. E. POWELL, president of Aluminum Company of Canada, Ltd., was a recent visitor to British Columbia where his company is investigating possible sites for establishment of a plant on the Pacific Coast.

HOWARD G. WILCOX, for 13 years on the faculty of University of Alaska, has resigned to accept a position as supervising mining engineer with the Reconstruction Finance Corporation.

GLEN E. FASSLER, lately employed as a mining engineer in the mining division of the Armco Steel Corporation, at Freeport, Texas, has returned to Honduras, where he will be chief engineer of New York and Honduras Rosario Mining Company's mining operations. He will be in charge of the company's silver mines in San Juancito and Mochito and at their new gold property in El Salvador.

ALFRED B. SABIN of San Francisco, California, recently returned from Afghanistan, where he made an industrial survey for that country's government.

BLAIR BURWELL, consulting mining and metallurgical engineer and a consultant for the Atomic Energy Commission, is now situated at Grand Junction, Colorado, where he is president of the newly organized Minerals Company. The firm is engaged in engineering and development work in connection with the uranium field in Colorado and Utah.

ROY A. ANDERSON can now be addressed at Cie. Aramayo de Mines en Bolivie, Casilla 674, La Paz, Bolivia.

ALFRED E. NUGENT, formerly with the Anaconda Copper Mining Co., has become manager of the Minah Development Co., at Helena, Mont.

LYMAN H. SHAFFER is professor of geology at the Superior State Teachers College, Superior, Wis.

JAMES A. ROWLAND, with the Bureau of Mines, has been transferred from Salt Lake City to Rolla, Mo.

OTTO D. ROHLFS, formerly principal mining engineer in the ferroalloys branch of the WPB, has a consulting mining engineering office in Seattle.

J. H. EAST, JR., was transferred in February from the Washington office of the Bureau of Mines to Denver, where he is in charge of the health and safety division.

R. S. BOTSFORD has been prospecting for barytes in Antigua and has done some core drilling. The barytes are for weighting oil-well mud in Trinidad.

JOHN J. COLLINS, mining geologist, returned to the States on a thirty-day leave from Japan, where he has been appraising copper deposits for the Supreme Commander of the Allied Powers.

JAMES B. MORROW has been elected president of Bituminous Coal Research, the national research agency of the bituminous coal industry, succeeding HOWARD N. EAVENSON.

LYSLE SHAFFER has resigned as an associate professor at the Missouri School of Mines and Metallurgy to accept the chairmanship of the department of mining at the South Dakota School of Mines and Technology, Rapid City.

G. T. WALTERS, after completing exploration and prospecting in the Koakeveld, South West Africa, finished his work as field manager of the Koakeveld Exploration Co. He then joined the geological staff of the Anglo American Corp. of South Africa at Johannesburg.

WILSON M. LAIRD, state geologist of North Dakota, was given the President's Award at the annual meeting of the A.A.P.G. at Denver. Mr. Laird received this citation along with L. L. Sloss, until recently professor of geology at the Montana School of Mines, for their joint work in preparing the report "Devonian System in Central and Northwestern Montana."

R. W. DIAMOND is the new president of the Canadian Institute of Mining and Metallurgy.

ARTHUR F. HAGNER, associate professor of geology, University of Wyoming, and assistant state geologist of Wyoming, has been appointed associate professor at the University of Illinois, where he will teach economic geology.

W. R. LINDSAY, consulting engineer, has left for British Guiana to begin an extensive development program for Cuyuni Goldfields, accompanied by FRANK BUCKLE, who will superintend the work.

P. DE HAART has been appointed chief inspector of mines of the Netherlands.

ROBERT S. LEWIS, head of the department of mining at the University of Utah, has retired and plans to devote some time to writing technical articles.

A. C. SKERL, formerly consulting geologist of the Cariboo Company, has joined the British Columbia exploration department of Noranda Mines.

H. M. LAVENDER, vice-president and general manager of the Phelps Dodge Corp., Douglas, Ariz., received one of the distinguished achievement awards presented to graduates of the Colorado School of Mines, Golden, Colo.

LANGBOURNE M. WILLIAMS, JR., president of the Freeport Sulphur Co. since 1933, has taken a leave of absence for an indefinite period so that he may assist Government officials in the administration of the Marshall Plan. He will act as director of the industry division in Europe for the Economic Cooperation Administration, with headquarters in Paris.

G. CARLETON JONES, of New Consolidated Gold Fields of South Africa, has been awarded the gold medal, the British Institute of Mining and Metallurgy's highest award for distinguished services to the South African mining industry, particularly for the West Rand development.

HANS MERENSKY, consulting mining engineer and geologist, received the Draper Memorial Medal for 1947, which is the Geological Society of South Africa's highest award for distinguished service.

A. P. FAWLEY has been appointed a geologist on the staff of the Mines Branch, Department of Mines and Natural Resources, of Manitoba, Canada.

J. M. PARKER of the geology department, North Carolina State College, Raleigh; L. J. CULP of Columbia University, New York; DONALD BROBST of the University of Minnesota, Minneapolis; and J. A. REDDEN of Dartmouth College, Hanover, N. H., are making their headquarters at the new office of the U. S. Geological Survey at Spruce Pine, N. C. The Survey is resuming its regular mapping operations in the area, which were suspended during the war.

JOHN E. BOWENKAMP has returned to Colombia from Brazil, where he was engaged in a mine examination assignment for Wellington Explorations, Ltd., a subsidiary of the N. A. Timnins Corp. of Montreal, Can.

E. R. RUDD has replaced R. LOCKHART JACK as chief geologist of the Broken Hill Proprietary Co., Australia. L. W. PARKIN, who resigned from the Department of Mines, Adelaide, is now senior geologist on the exploration staff of Broken Hill.

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